CO_2 From Direct Air Capture For Greenhouse Horticulture

Extras

WAGENINGEN
UNIVERSITY & RESEARCH

Before You Dive In

This publication is meant to help close the gap between greenhouse growers and Direct Air Capture (DAC) providers – and more generally, any other suppliers offering CO_2 solutions. Companies operating outside the horticulture sector often have limited insight into how CO_2 is applied in practice: the quantities used, the timing of dosing, target concentrations within the greenhouse, and other operational specifics. As a result, CO_2 suppliers and growers often "speak different languages." For example, growers typically express their CO_2 demand in kilograms per hour per hectare, while DAC suppliers express their production capacity in terms of kilograms per day.

By offering key figures and contextual explanations, this document aims to support CO_2 suppliers in gaining a better understanding of the greenhouse horticulture sector, while also helping growers to become more familiar with the principles and potential of Direct Air Capture.

Suppliers Growers

Before You Dive In

How Greenhouses Use CO_2 And Why It's Becoming A Challenge

About The Project 'Innovation and Demonstration Center CO_2 From Direct Air Capture For Horticulture'

About Wageningen Plant Research & The Business Unit Greenhouse Horticulture

How Greenhouses Use CO_2 – And Why It's Becoming A Challenge

For decades, Dutch greenhouses have used CO_2 to boost crop growth. Figure 1 shows the yield increase achieved at higher CO_2 concentrations compared to the current outdoor level (approximately 425 ppm).[1] It also illustrates how significantly crop growth decreases when CO_2 levels fall below this outdoor concentration. In most greenhouses, natural ventilation through windows is often insufficient to maintain a CO_2 level equal to the outdoor concentration.[2,3]

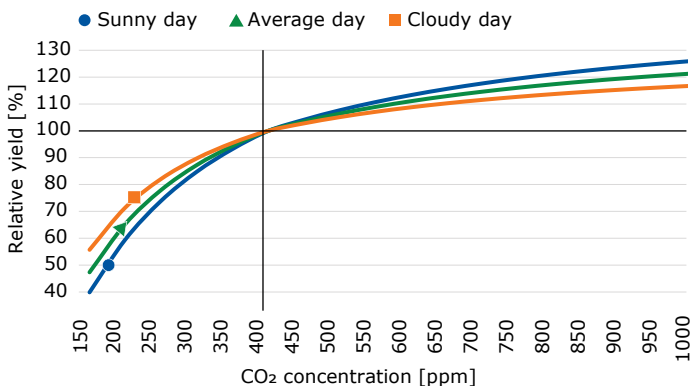

Figure 1: Relative production (%) of greenhouse fruit vegetable crops as function of the average CO_2 concentration (ppm) in the greenhouse during cultivation. Production at 425 ppm as point of reference (100%). Source: Adapted from Nederhoff (1994).[10]

Today, most CO_2 dosed in greenhouses comes from burning natural gas in combined heat and power units on-site (CHP), or from nearby industry via pipelines (OCAP).[4] As the energy transition moves forward—driven by climate policies and the horticulture sector's own goal to stop using fossil fuels—the availability of CO_2 from CHP is expected to decrease.[5] On top of that, the supply of external CO_2 for greenhouses may also shrink, depending on how climate policies are put into practice. Industries that currently provide CO_2 to horticulture are required to cut their own emissions. As a result, storing CO_2 permanently (CCS) may be prioritized over reusing it (CCU).

A project currently under development by Porthos focuses on transporting and storing CO_2 from industries in the Rotterdam port area. The CO_2 will be stored in depleted gas fields under the North Sea. Construction of the necessary infrastructure began in early 2024, with the system expected to be operational in 2026. Porthos is collaborating with four clients: Air Liquide, Air Products, ExxonMobil, and Shell. Northern Lights is a similar initiative in Norway, where CO_2 emissions from Yara Sluiskil will be stored.

To maintain the current productivity and efficiency of greenhouse horticulture, the sector is exploring solutions: using CO_2 more efficiently and finding new, more sustainable sources. The Dutch greenhouse sector requires around 2.6 million tonnes of CO_2 annually, with 2 million tonnes expected to come from sustainable sources by 2030.[4,6]

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This publication is part of the Innovation and Demonstration Center CO_2 from Direct Air Capture for Horticulture. The project provides a platform for the independent evaluation of DAC technologies. During the project, multiple DAC companies have the opportunity to install their system within the greenhouse facilities of Wageningen University & Research, located in Bleiswijk (the Netherlands). The trials are open for demonstration purposes, allowing interested parties to visit the test setup and experience the operation of the systems in practice.

The research focuses on collecting data in a practice-oriented environment to gain the following insights:

- **CO_2 quality from DAC:** Identifying potential risks related to phytotoxic gases and outlining measures that DAC companies and growers can implement to mitigate those risks.
- **Performance characteristics:** Analysing how DAC machines perform under different climate conditions, paying specific attention to:
  - The concentration of CO_2 delivered;
  - Achieved capacity;
  - Production pattern (continuous or batch);
  - Energy consumption per kilogram of captured CO_2.
- **Consumables:** Assessing the quantity and sustainability of required inputs, such as sorbents and filters.
- **By-products:** Investigating the quantity and quality of outputs, such as condensate water.

Opening of the Innovation and Demonstration Center CO_2 From Direct Air Capture For Horticulture by the Dutch minister of agriculture Piet Adema. Source: Fotostudio Vlekke

- **Practical implementation:** As the technical characteristics of commercial DAC technology become clearer, analysis will focus on how CO_2 production can best match the demand of various greenhouse cultivations. This includes consideration of potential CO_2 buffer capacity and the availability and cost of (renewable) heat and electricity.
- **Economic outlook:** Based on energy efficiency (kWh/kg CO_2), energy prices, and CO_2 dosing strategies, the economic viability can be assessed. If possible, depreciation of equipment and costs for consumables and maintenance could be included.

The overall aim of the project is to demonstrate and develop knowledge on the feasibility and effectiveness of DAC technology in the greenhouse horticulture sector, with the goal of making CO_2 use more sustainable.

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The business unit Greenhouse Horticulture works together with companies and governments to create a fully sustainable, economically viable horticulture sector that is fossil-free, closes the water cycle, minimizes pesticide use, and optimizes circular use of resources. CO_2 – the focus of this document – is one of the key material flows we research, particularly within our Circular Horticulture programme.

With state-of-the-art research greenhouses and labs in Bleiswijk and Wageningen, we are deeply immersed in every aspect of greenhouse horticulture: crop management, supply chains, technical systems, automation, AI and innovative greenhouse design.

Click here to read more or get in touch.

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Welcome CO_2 Suppliers

This publication is designed with you — supplier of CO_2 solutions — in mind. Whether you're working with Direct Air Capture (DAC) technology or another CO_2 solution, we experienced first-hand that it can be challenging to align with the needs of greenhouse growers. The horticulture world has its own way of operating when it comes to how CO_2 is used: the quantities, when it's dosed, target concentrations within the greenhouse, and other operational specifics.

Coming from different industries, CO_2 suppliers and growers often "speak different languages." For example, growers typically express their CO_2 demand in kilograms per hour per hectare, while DAC suppliers express their production capacity in terms of kilograms per 24 hours. That's why this document brings together practical data and context to help bridge that gap. Our goal is to give CO_2 suppliers a clearer picture of how the greenhouse sector operates, and in doing so, make collaboration smoother and more effective.

In the navigation menu you can find an overview of the topics discussed in this document, or simply use the arrow buttons you see below.

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CO_2 Properties

Carbon dioxide (CO_2) is a gas that's naturally present in the atmosphere and is also emitted by human activities like burning coal, oil, and gas. CO_2 is widely used in various sectors as a resource: in greenhouse horticulture to boost crop growth, in the food and beverage industry for carbonating drinks and preserving packaging, in fire extinguishers as a suppressant, and even in water treatment. Yet, CO_2 is also a major greenhouse gas—trapping heat in the atmosphere and driving climate change. This makes it both a valuable resource and a critical environmental concern. However, the properties of CO_2 are constant, and having them at hand can be useful for making simple estimations or discussing various scenarios.

Several online tools, such as the NIST Chemistry WebBook, are available to view and calculate properties of CO_2.

- Chemical formula: CO_2
- Appearance: Colourless as a gas and liquid, white as a solid.
- Odour: At low concentrations it is odourless, but at high concentrations it has a sharp acidic smell.
- Flammability: Non-flammable
- Solubility: Carbon dioxide is soluble in water in which it reversibly forms carbonic acid (H_2CO_3).
- Molecular weight: **44.01 g/mol**
- Density – Gas: CO_2 is about 1.5 times heavier than air. In gaseous state at 20 °C and 1 atm (NTP) CO_2 has a density of **1.84 kg/m³**. Reversely, 1 kg of CO_2 occupies a volume of about **0.54 m³**.
- Density - Liquid: CO_2 only exists as a liquid within a temperature range of -56.6 °C and 31 °C and pressures between 5.2 bar and 74 bar. Fully saturated at –37 °C and 11 bar, liquid CO_2 has a density of **1100 kg/m³**.
- Density - Solid: Solid CO_2 is also referred to as "dry ice" and forms at atmospheric pressure below the boiling point of -78.5 °C. It has a density of **1560 kg/m³**.
- Boiling point: At atmospheric pressure solid CO_2 sublimes at -78.5 °C, meaning that it passes directly from solid to gaseous state.
- Critical temperature: 31 °C
- Critical pressure: 74 bar
- Triple-point temperature: -56.6 °C
- Triple-point pressure: 5.2 bar

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CO_2 & Photosynthesis

CO_2 is often added to greenhouses to stimulate crop growth and increase yields. But why does it work? Here's a brief explanation of the underlying biological processes that make CO_2 enrichment such an effective tool.

Photosynthesis is the process by which plants use **light energy** to convert **carbon dioxide (CO_2)** in presence of **water (H_2O)** into **glucose ($C_6H_{12}O_6$)** and **oxygen (O_2)**. This happens mainly in the leaf cells and can be summarized as:

$$6CO_2 + 6H_2O + PAR\ light \rightarrow C_6H_{12}O_6 + 6O_2$$

Photosynthesis occurs in two main stages: **the light-dependent reactions and the Calvin Cycle**.

1 In the light-dependent reactions, chlorophyll captures light energy and converts it into energy-rich molecules such as ATP and NADPH.
2 In the Calvin Cycle, the enzyme **RuBisCO** uses this stored energy to fix atmospheric CO_2 into sugars.

RuBisCO, however, can also **bind O_2 instead of CO_2**. When O_2 is bound, the plant enters **photorespiration**—a process that consumes energy and releases CO_2 without producing sugars. This **reduces overall photosynthetic efficiency**.

The likelihood of RuBisCO binding O_2 rather than CO_2 depends strongly on the relative concentrations of these gases in the leaf. At **higher ambient CO_2 levels**, the ratio of CO_2 to O_2 increases, making it more likely that RuBisCO will bind CO_2. This **suppresses photorespiration**, allowing more of the absorbed light energy to be used for sugar production.

Figure 2: A single stoma that can open and close. Stomata are tiny pores, mainly on the underside of leaves, that regulate the uptake of CO_2 and the release of O_2 and water vapor. Click on the image to see the video of a stoma opening and closing! Source: Douglas Clark

When light is abundant, CO_2 often becomes the limiting factor for photosynthesis. Enriching the air around plants with CO_2 increases the rate of photosynthesis by reducing the energy lost to photorespiration. The result is faster sugar production, greater growth, and higher yields—provided that other growth factors (light, water, nutrients, temperature) are also sufficient.

How does this knowledge help in developing DAC systems for horticulture? There are different types of crops, and most of those grown in greenhouses are either C3 or C4 plants. These plants only benefit from additional CO_2 when there is light available—either during the day or when artificial lamps are on. Key points to consider are:

- There is **no CO_2 demand during the night** because photosynthesis does not occur without light.
- **CO_2 demand fluctuates** throughout the day and seasons, **depending on light intensity**.
- An exception to this pattern is CAM plants, which actually absorb CO_2 during the night (the dark period).

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CO_2 Metrics In Horticulture

CO_2 concentration

- **ppm (parts per million)** CO_2 concentrations in air are usually expressed as ppm. For instance, present atmospheric CO_2 concentration is around **425 ppm**. In greenhouses, growers often aim for higher CO_2 concentrations—**up to 1200 ppm**—depending on the crop.
- **% (percentage by volume)** CO_2 supplied by industry is usually expressed as a percentage of the total volume of the gas mixture. Currently, greenhouses use CO_2 from:
  - Flue gases of CHP: 5-6% (=50,000-60,000 ppm)[18]
  - OCAP: 98-100% (=990,000-1,000,000 ppm)
  - Pure, liquified CO_2: 99-100% (=990,000-1,000,000 ppm)

Why does concentration matter?
In principle, greenhouses can use any CO_2 concentration above the desired indoor level. However, the **concentration of the CO_2 supply strongly influences the required gas volume**. For example, raising the CO_2 level in a greenhouse using a gas flow containing only 1,000 ppm CO_2 requires significantly more volume than using a stream of pure CO_2. The inverse relationship between CO_2 concentration and required volume has two key implications:

1 **Low-concentration CO_2 is generally unsuitable for storage**, because the large volumes required make it impractical and/or cost-prohibitive. DAC systems that (only) produce low-concentration CO_2 must therefore supply CO_2 in sync with real-time CO_2 demand of a greenhouse. CO_2 demand in greenhouses mainly occurs during the light period. In the Netherlands, many growers use artificial lighting, which extends the period of CO_2 demand, though night-time demand remains minimal. Also see the section on CO2 Storage.

2 **Dosing low-concentration CO_2 requires large gas volumes**, and if the supplied gas mixture is colder or warmer than the greenhouse air, this may affect the greenhouse climate and increase a grower's overall energy costs.

The optimal CO_2 concentration for a DAC system to produce is a cost-benefit trade-off, influenced by real-time CO_2 demand, achievable production capacity, purification and storage costs, and any additional energy use.

CO_2 dosing

CO_2 dosing refers to the amount of CO_2 introduced into the greenhouse per unit of time and area. It is usually expressed in **kilogram per hectare greenhouse per hour (kg/ha/h)** and typically ranges from **25 to 250 kg/ha/h**. On an annual basis the dosed CO_2 is often expressed as kg per m^2 greenhouse ($kg/m^2/y$).

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CO_2 uptake by crop

The CO_2 uptake by photosynthesis is usually expressed as **grams per m² greenhouse per hour (g/m²/h)** and can reach up to **7 g/m²/h**, or **70 kg/ha/h**. CO_2 uptake rates depend on crop type, light- and CO_2-levels. More information can be found in the section CO_2 Use Crops.

Why do growers dose more CO_2 than what the crop takes up?

Growers generally need to supply (much) more CO_2 than the crop actually absorbs. This is because greenhouses aren't airtight – CO_2 escapes through leaks. Vents are also opened intentionally to regulate temperature or humidity. More information can be found in the section Efficiency – CO_2 Crop Uptake Versus CO_2 Dosing.

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Key Aspects Of DAC & Horticulture

The list below outlines key aspects of DAC technology and greenhouse horticulture to support technical discussions on feasibility and suitability. It can also serve as a questionnaire to help clarify expectations, technical requirements, and assess the potential match between CO_2 supply and demand.

DAC parameters	Units	Why is it important?
Total energy use *Electricity use *Heat use	kWh/kg CO_2 kWh_e/kg CO_2 kWh_{th}/kg CO_2	Major influence on OPEX and therefore the cost per kg of CO_2 for the grower. Some growers have access to geothermal wells or heat grids, making the type of energy that a DAC system requires an important consideration.
Required power connection	single-phase or three-phase? Voltage (V) Amperage (A)	Provides an indication for required grid capacity. (At the time of publication, grid capacity is an issue in some parts of the Netherlands.)
Required heating capacity	kW	Indicates the required heating infrastructure and the potential to integrate with existing greenhouse heating systems. If the DAC system can use hot water, it's useful to note that Dutch growers typically have different supply temperatures depending on the source: around 40 °C with a heat pump, up to 70 °C with a CHP or boiler, and around 80 °C with geothermal. The return temperature from the DAC system helps determine whether the residual heat can still be used effectively within greenhouse operations.
Required heating temperature and return temperature	°C	
Required cooling capacity	kW	Some growers have cooling capacity available.
Desired cooling temperature and return temperature	°C	
Production capacity per machine or module	kg/h	Gives growers a general idea of how many machines they need for their cultivation, and indicates potential CO_2 storage size.
CO_2 concentration	ppmv or % vol.	Provides insight into required dosing volumes and whether CO_2 can be produced and stored during periods of low or no demand—potentially reducing costs when energy prices are low. In some cases, even seasonal storage may be a viable option.

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DAC parameters	Units	Why is it important?
Volume output	m^3/hour	The volume of CO_2 or gas mixture produced influences the type and size of piping required for transport and dosing within the greenhouse.
Pressure	bar	Depending on the pressure, different CO_2 dosing systems may be more appropriate or effective.
CO_2 temperature	°C	Growers typically allow some temperature variation, but if the CO_2 supply differs significantly from the greenhouse temperature, it may affect the crop or disrupt climate control systems—especially when large volumes are dosed.
Moisture content	g/m^3	May cause condensation (linked to dew point temperature), which can promote fungal diseases in the greenhouse. Excess moisture can also disrupt climate control. This is especially important when large volumes of CO_2 are dosed, as is more often the case with low-concentration CO_2.
Mode of operation Startup and shutdown time	Continuous or batch? minutes	The mode of operation affects integration with the greenhouse CO_2 demand profile. Under mid to high light conditions and closed vents, a fully grown crop can deplete the CO_2 inside a greenhouse in a matter of 30 minutes! A short startup and shutdown time makes for easy and flexible control.
Dimensions	Length, width and height (m)	Limited available space can be a constraint for some growers, and local building regulations—such as height restrictions—should also be taken into account.
Weight	kg/m^2	Indicates whether additional foundation work is required, which may lead to extra costs.
Intake air quality	N/A	While DAC systems typically include air filters, local air quality can still influence performance. Factors such as proximity to industrial areas, highways, and the presence of dust or pollen can affect filter load and maintenance needs.
Other outputs	N/A	Are there any by-products besides CO_2 that growers should be aware of, such as wastewater, other gases, or hazardous waste materials?
Maintenance	N/A	What maintenance is required and what are the costs? Especially the life expectancy of the sorbent or solvent is key.

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Greenhouse parameters	Units	Why is it important?
Energy sources	N/A	Depending on the available energy sources, a DAC supplier may adapt their system to use them efficiently. Sustainable options a grower may have access to include geothermal energy, heat grids, heat pumps, thermal energy storage, solar panels, and wind turbines.
Available temperature heating water	°C	Indicates whether the existing heating water can be used directly or requires upgrading to a higher temperature to meet the DAC system's requirements.
CO_2 demand	kg/ha/h or kg/h	Ultimately, the hourly CO_2 demand data of a greenhouse offers the most valuable insights into how to best align CO_2 supply from a DAC system with the greenhouse's actual needs.
Target and achieved CO_2 levels	ppm	Shows what a grower is aiming for and if they realize their target.
Climate computer	N/A	The type of climate control system and software provider may be relevant for the DAC supplier to ensure seamless integration and control.

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CO_2 Use Of The Dutch Greenhouse Horticulture Sector

The Dutch greenhouse horticulture sector currently uses around **2.6 million tonnes of CO_2 annually**.[4] Glastuinbouw Nederland – the industry association representing the sector – aims for 2 million tonnes to come from sustainable sources by 2030.[6] Naturally, actual CO_2 use will depend on factors like the total greenhouse area, improvements in dosing efficiency, and developments in CO_2 pricing.[7]

Not every crop uses the same amount of CO_2. Figure 3 shows the average annual CO_2 use and greenhouse area by subsector in Dutch greenhouse horticulture. **Fruits and vegetables generally use the most CO_2** and constitute the largest greenhouse area, therefore accounting for 64% of total demand. For specific CO_2 Use Crops please see section CO2 Use Crops.

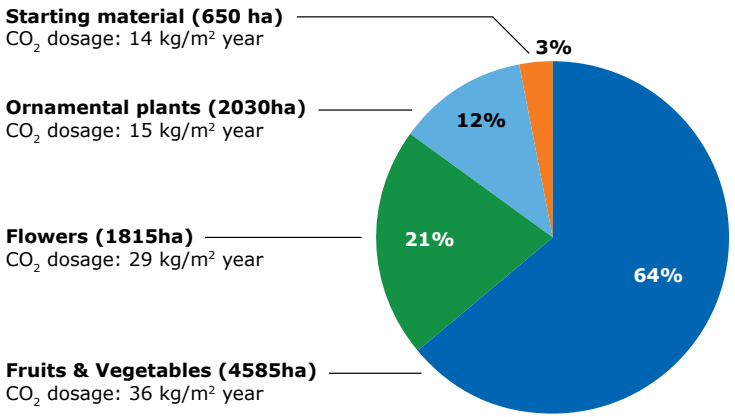

Figure 3: Average annual CO_2 dosage (kg/m²/y) and greenhouse area (ha) by subsector in Dutch greenhouse horticulture. The percentages indicate each subsector's share of the total annual CO_2 use, which amounts to 2.6 million tonnes. Source: Adapted from Van der Velden, N. J. A., & Smit, P. X. (2019).[4]

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CO_2 Use Per Crop

CO_2 use varies per crop. Figure 4 shows average annual CO_2 dosage per crop, with and without supplemental lighting. Among vegetables, high-wire crops like tomato, bell pepper, cucumber, and eggplant are the highest users, averaging 40–50 kg/m²/y. In ornamental crops, roses and gerberas also show high usage, even up to 80 kg/m²/y.

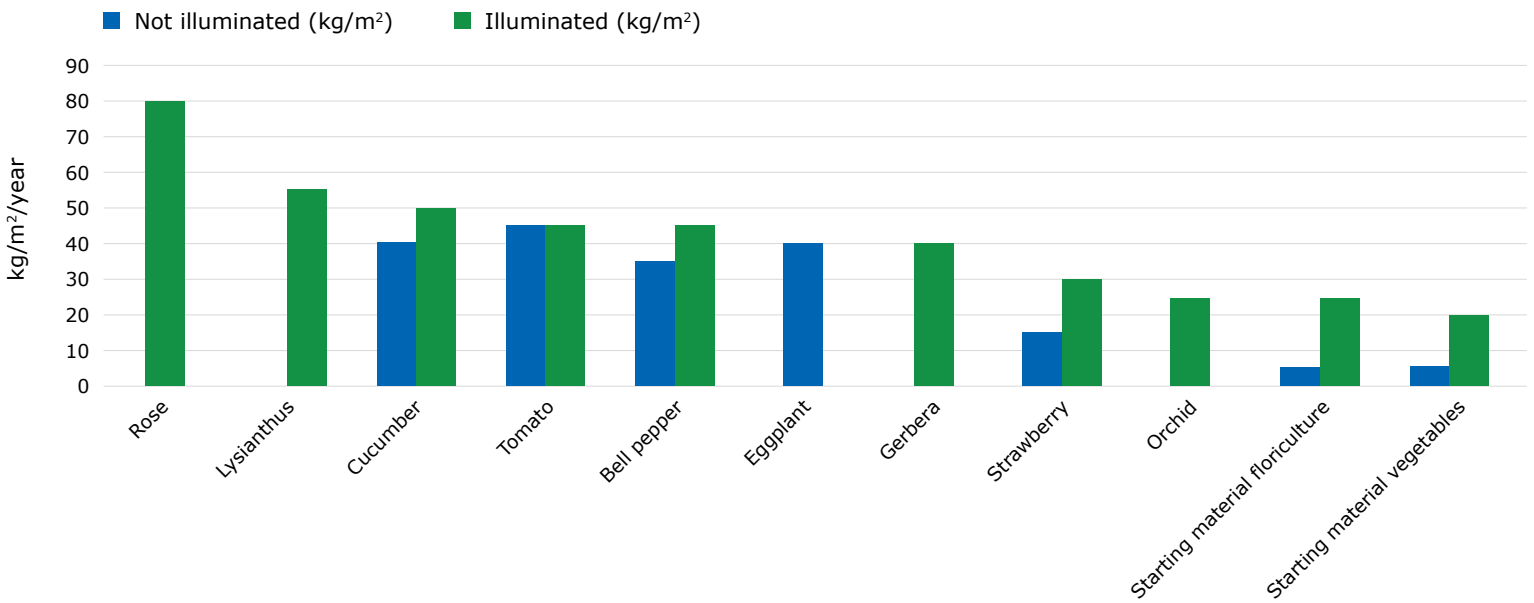

Figure 4: CO_2 dosage per crop, with and without supplemental lighting. Source: Adapted from Van der Velden, N. J. A., & Smit, P. X. (2019).[4]

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Dosing CO_2 In A Greenhouse

Depending on the crop, growers typically aim to increase CO_2 levels in their greenhouse to around **600–1200 ppm**. How do they do it?

Current CO_2 Sources And Dosing Systems

To understand how CO_2 is dosed in greenhouses we have to start at the source. A common CO_2 source in greenhouses is the Combined Heat and Power (CHP) unit, which many growers use for electricity, heating, and CO_2. **CHP systems** produce **flue gases** with about **5% CO_2** (or 50,000 ppm). When CO_2 is needed, these gases are cleaned and distributed into the greenhouse using fans. A typical CHP system (2 MW_e) produces around **970 kg CO_2 per hour**, with flue gas flow rates of about **2850 m³/ha/h**. Distribution is typically done through **perforated plastic tubing** (layflat LDPE or HDPE tubing) with a width of **65–120 mm**. The tubing is usually placed **below or within the crop canopy**.

A Combined Heat and Power (CHP) unit running on (natural) gas simultaneously produces heat, electricity, and CO_2. The thermal energy heats the greenhouse, while the generated electricity is either used on-site for supplemental lighting or fed into the power grid. The resulting CO_2 can be partially utilised inside the greenhouse to stimulate crop growth, with any surplus released to the atmosphere.

CO_2 is dosed via plastic tubing below a raspberry crop.

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OCAP realises a new underground CO_2 pipe connecting greenhouse area De Kwakel at Aalsmeer to their grid in 2022. Source: Wilmar Dik in accordance with OCAP

Impression of a tank installation for liquid CO_2 delivery and storage at a greenhouse. Source: ChatGPT

Another common source of CO_2 in Dutch greenhouse horticulture is OCAP (Organic CO_2 for Assimilation of Plants). OCAP generates **near-pure CO_2** (≥98%, or 980,000 ppm) from industrial emitters and distributes it to growers via a **dedicated pipeline network**. The CO_2 arrives at the greenhouse and is reduced from 16-22 bar to a pressure of **2–3 bar**. Growers then dose the CO_2 into the greenhouse using perforated plastic tubing, typically **20–30 mm** in diameter, positioned between or below the crop canopy for even distribution.

A third CO_2 source, less commonly used in the Netherlands, is liquid CO_2 delivered by truck and stored on-site in insulated tanks. Typical storage capacities range up to 5–10 m³ per hectare, depending on crop demand and delivery frequency. The liquid CO_2 is vaporized and dosed into the greenhouse through perforated tubing (usually 20–30 mm in diameter), at a pressure of around 2–3 bar.

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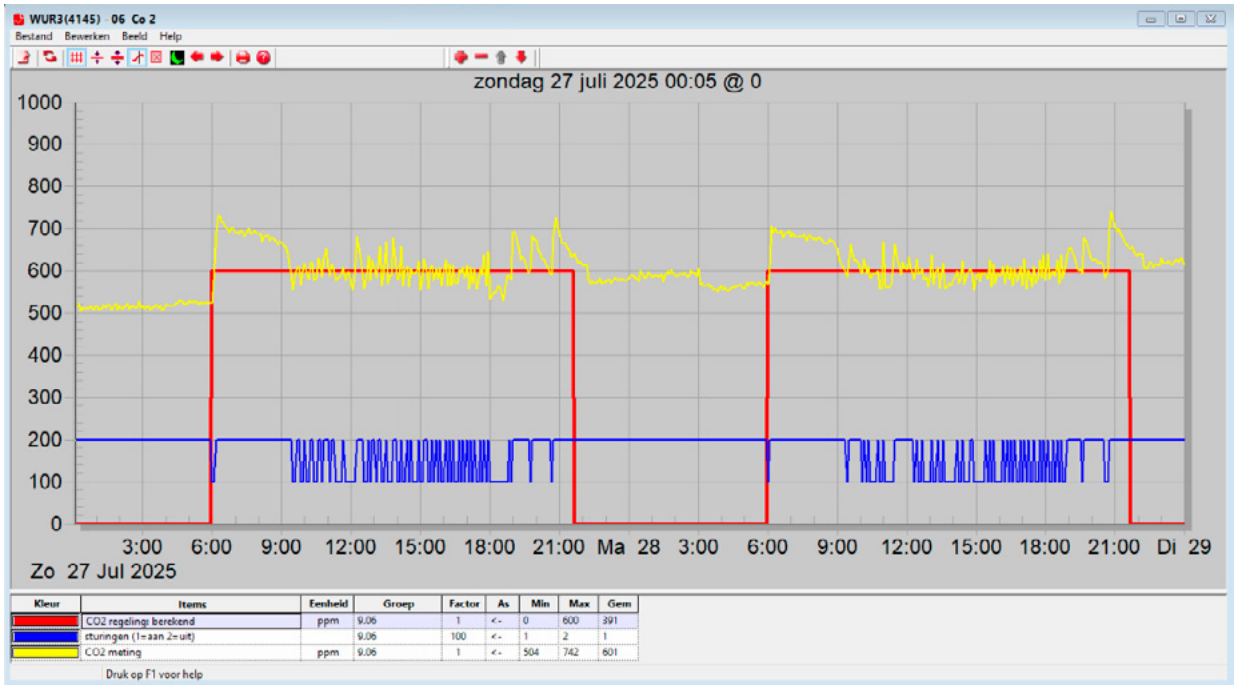
CO_2 Monitoring And Control

Greenhouses are equipped with CO_2 sensors connected to a climate computer, where growers set their desired CO_2 levels. These setpoints can adjust dynamically—for example, lowering the target when vents open or increasing it with rising light levels. The sensors provide real-time CO_2 data. When levels drop below the target, the climate computer activates dosing by opening valves. Typically, 1–2 sensors per hectare are used for monitoring.



Screenshot of CO_2 monitoring and control settings in a climate computer. Yellow line: measured CO_2 concentration in the greenhouse. Red line: CO_2 target setpoint. Blue line: status of the CO_2 dosing valve (open/closed).

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Seasonal Variation In CO_2 Use

CO_2 use in greenhouses **varies seasonally** with light availability and ventilation. In spring and summer, higher sunlight levels stimulate plant growth and photosynthesis, increasing CO_2 use. During these warmer months, open windows and higher ventilation rates cause more CO_2 to be lost, further raising consumption. In contrast, during autumn and winter, lower light levels slow plant growth, and with windows mostly closed, less CO_2 escapes through ventilation, resulting in lower overall demand.

Figure 5 shows the variation in **average daily CO_2 dosage** throughout the year for a **tomato** greenhouse without supplemental lighting. The numbers in the graph reflect a commercial greenhouse with a **maximum CO_2 dosing capacity of 200 kg/ha/h** and natural ventilation to control temperature and humidity. The graph shows three scenarios, each representing a different target CO_2 concentration inside the greenhouse. For each scenario, the total annual CO_2 dosage is also indicated, illustrating how target levels influence overall CO_2 use.

The difference between summer and winter is significant — especially when aiming for higher CO_2 levels in the greenhouse. As shown in the graph, on **bright summer days** a grower may dose **>2,500 kg/ha/d**, while on **dark winter days <300 kg/ha/day** is sufficient.

A tomato crop **with supplemental lighting** would show **relatively smaller seasonal fluctuations** in CO_2 demand. This is because artificial lighting compensates for the lack of natural light in autumn and winter, boosting photosynthesis—

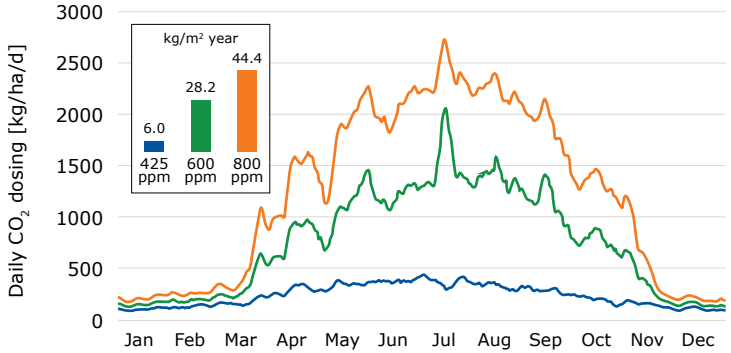

Figure 5: Average daily CO_2 dosage over a year in a tomato greenhouse without supplemental lighting, based on target concentrations of 425, 600, and 800 ppm. Total annual CO_2 consumption is indicated for each scenario, showing how higher setpoints increase overall use.

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and with it, CO_2 uptake. However, the general trend of (much) lower CO_2 demand in the darker months still applies to most crops.

That said, some crops have a more consistent CO_2 demand throughout the year. **Gerbera**, for example, is a **short-day plant that requires strict light–dark cycles**, typically maintained with supplemental lighting. It is also shade-tolerant and can be damaged by excessive direct sunlight. Figure 6 shows the seasonal CO_2 dosage pattern for gerbera grown under supplemental lighting. The graph includes two CO_2 dosing strategies: one with a lower, more conservative dosing rate and one with a higher maximum dosing capacity. Note: gerbera is a multi-year crop. The curve shown is intended to illustrate the overall pattern compared to tomato cultivation without supplemental lighting; actual CO_2 dosing strategies vary per grower, cultivar, and growing cycle.

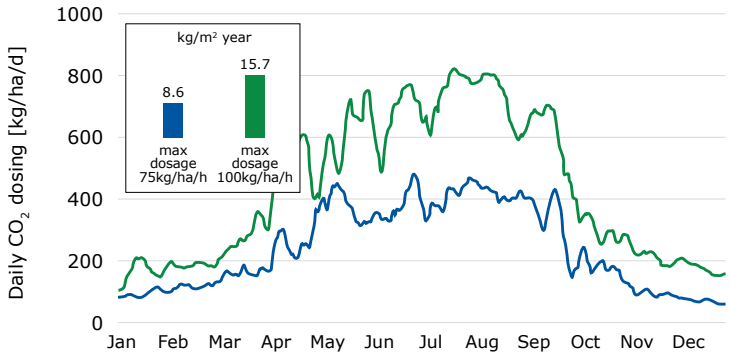

Figure 6: Average daily CO_2 dosage over the year for a gerbera greenhouse with supplemental lighting, based on maximum dosing capacities of 75 and 100 kg/ha/h. Total annual CO_2 consumption is indicated for each scenario, showing how higher setpoints increase overall use.

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Daily Variation In CO_2 Use

As explained in the previous section, seasonal variation in **CO_2 use is largely driven by the availability of natural light**. The same principle applies on a daily scale: as light levels rise, so does the crop's CO_2 uptake. During the dark period, CO_2 is generally not dosed, and most crops actually release CO_2 through respiration. Figure 7 illustrates the CO_2 dosing pattern in a tomato greenhouse without supplemental lighting on a clear summer day (left) and on a variable day with intermittent cloud cover (right). As soon as the sun rises, CO_2 dosing begins to increase, matching the onset of photosynthesis, and it stops again when the sun goes down. The graphs clearly illustrate how CO_2 dosing follows light availability — higher radiation leads to higher dosing.

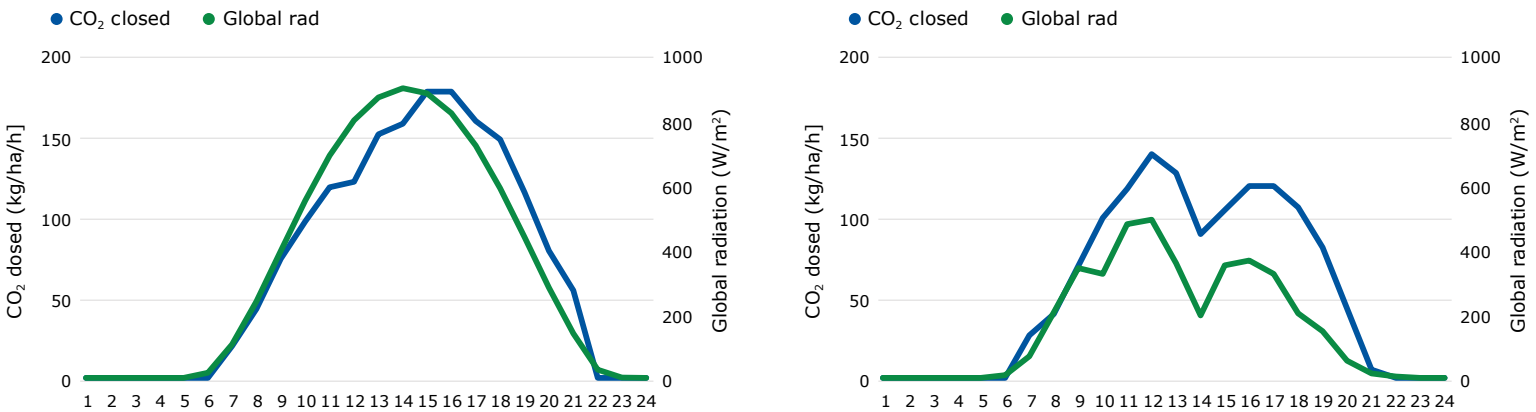

Figure 7: CO_2 dosing in a tomato greenhouse without supplemental lighting: clear summer day (left) versus variable day with intermittent clouds (right). Dosing follows light availability — increasing after sunrise, decreasing with cloud cover, and stopping at sunset.

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Efficiency - CO_2 Dosing Versus CO_2 Crop Uptake

CO_2 Crop Uptake

CO_2 uptake by crops can vary widely, depending not only on the crop species but also on growing conditions such as light intensity, how much light the crop can intercept, and the CO_2 concentration in the greenhouse.

For example, cucumber can absorb around 7 g CO_2/m²/h under high light conditions (1000 µmol/m²/s PAR) and high CO_2 levels (≥ 700 ppm). Under lower light (500 µmol/m²/s PAR) but the same CO_2 level, this drops to about 4 g CO_2/m²/h.[8]

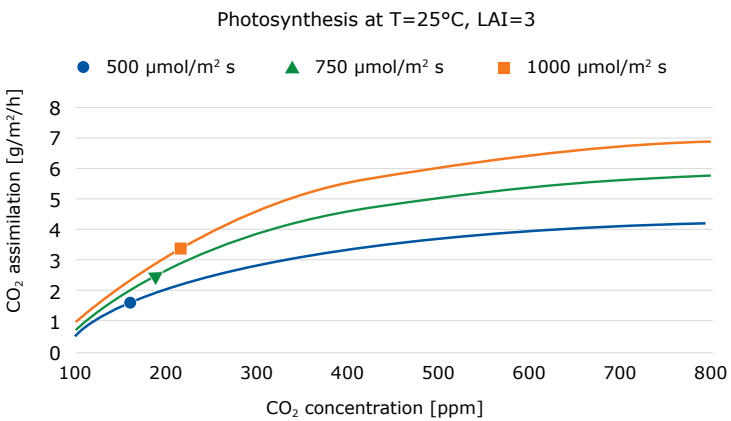

Figure 8: Net photosynthesis (g/m²/h) of cucumber at various light levels and CO_2 concentrations. Source: Adapted from Hogewoning (2024).[8]

Figure 8 shows the CO_2 assimilation (also known as the photosynthesis curve) for cucumber under various light and CO_2 levels. It's clear that photosynthesis generally increases with higher CO_2 concentrations. However, the relationship is not linear — there is a limit to how much extra CO_2 a crop can use. So, while increasing CO_2 can boost yield, the benefits level off at higher concentrations.

Keep in mind that cucumber has a relatively high light use efficiency (LUE). In other words, it converts light and CO_2 into growth more effectively than many other crops. In contrast, LUE can be much lower in other species, particularly in some floricultural crops, where maximum photosynthesis rates can be less than half of those observed in cucumber.[9]

CO_2 dosing

In theory, if CO_2 dosing were matched exactly to crop uptake, there would be no losses—every molecule of CO_2 would be assimilated by the plants. However, this assumes a perfectly sealed greenhouse, which is not the case in practice.

In reality, greenhouses experience continuous CO_2 losses due to:

- Infiltration (leakage): typically around 5,000 to 10,000 m³/ha/h, depending on construction quality, size, and wind conditions.
- Intentional ventilation: used to regulate temperature and humidity, which also releases CO_2 into the outside air. Depending on vent opening and wind speed, ventilation rates can go up to 60,000 m³/ha/h.

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As a result, the more ventilation occurs, the lower the efficiency of CO_2 dosing—since a larger portion of the supplied CO_2 escapes before it can be used by the crop.

Efficiency

Figures 9 through 11 show the CO_2 uptake by a tomato crop in a high-tech, semi-closed Dutch greenhouse compared to CO_2 losses through ventilation. Three scenarios are illustrated:

maintaining the greenhouse at the ambient outdoor concentration of 425 ppm, and increasing the target concentration to 600 ppm and 800 ppm.

Figure 9 shows that maintaining the greenhouse CO_2 concentration at the outdoor level (425 ppm) requires approximately 60 tons/ha/y, with minimal losses to the outside. Yield reaches 67 kg/m^2 per year. Efficiency is defined as the percentage of the dosed CO_2 that is assimilated by the crop.

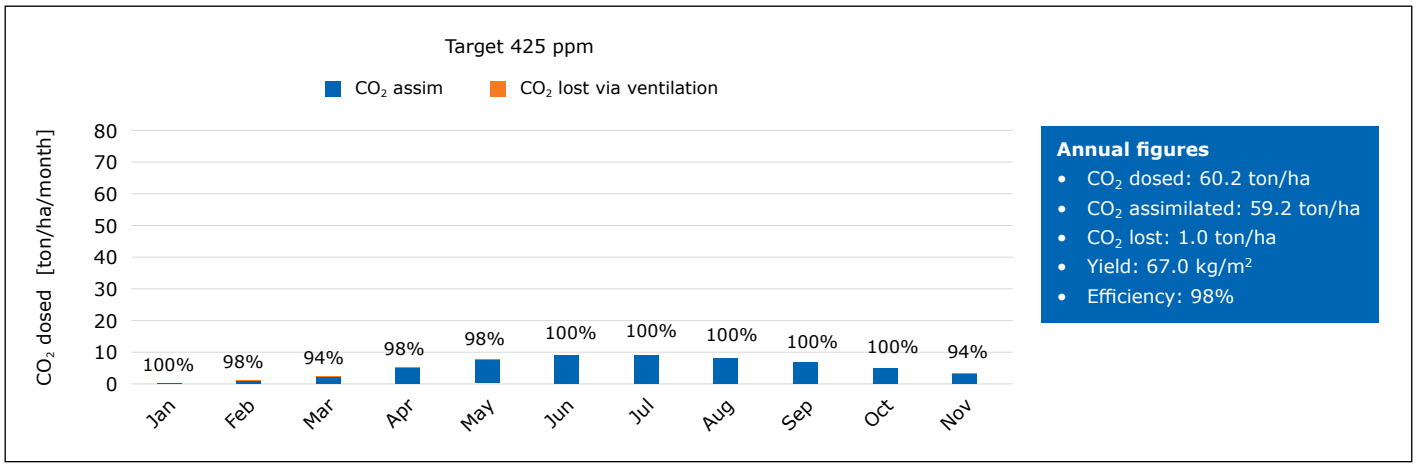

Figure 9: Maintaining the greenhouse CO_2 concentration at the outdoor level (425 ppm) requires approximately 60 tons/ha/y, with minimal losses to the outside. Efficiency is defined as the percentage of the dosed CO_2 that is assimilated by the crop.

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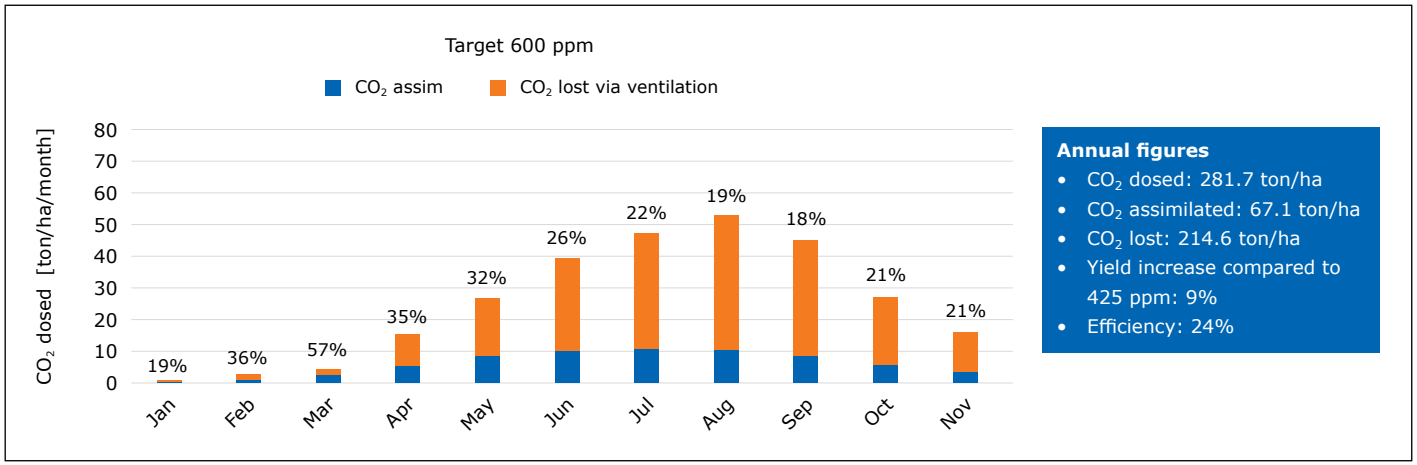

Figure 10: Raising the CO_2 target concentration to 600 ppm, requires much more CO_2 compared to maintaining 425 ppm. Dosing efficiency drops to 24%, but yield increases by 9% compared to 425 ppm due to higher CO_2 assimilation by the crop.

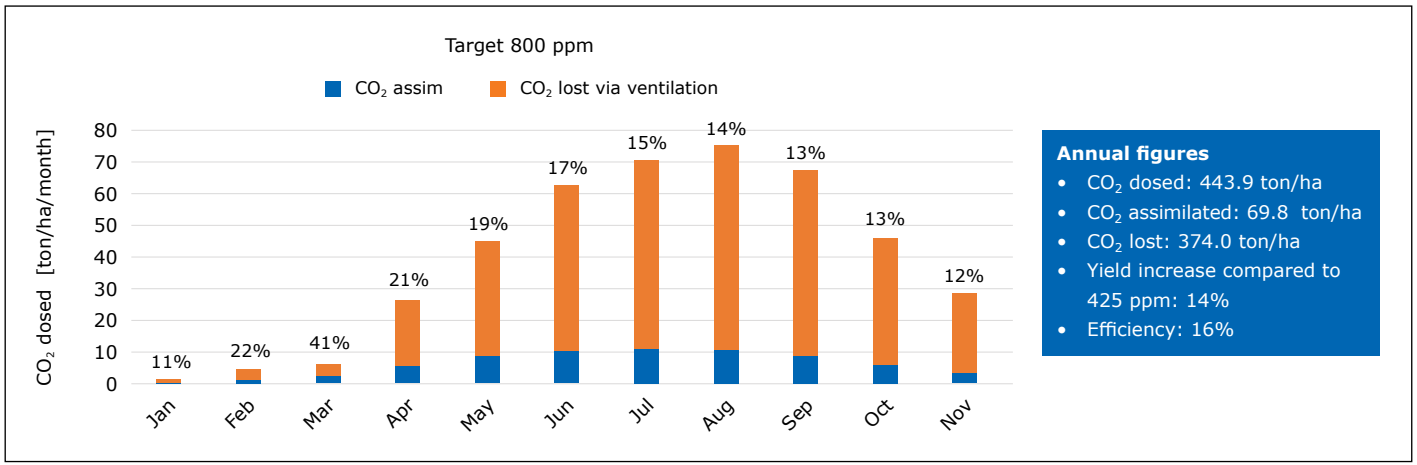

Figure 11: At a target of 800 ppm, dosing efficiency drops to 16%, while yield increases by 14% compared to 425 ppm. However, the yield gain from increasing CO_2 from 600 to 800 ppm is smaller than the gain from 425 to 600 ppm. This reflects the non-linear response of photosynthesis to CO_2: the curve levels off, meaning additional CO_2 results in diminishing returns in crop growth (see Figure 8).

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CO_2 Quality

While CO_2 is essential for plant growth, certain gases—known as phytotoxic gases—can harm plants even at very low concentrations. For DAC suppliers targeting the greenhouse sector, it's important to ask: "**Can I guarantee that my system does not emit by-product gases that could harm plants or humans?**" Two potential sources to consider:

1 Could the system's processes (e.g., heating, cooling, vacuum) cause material degradation or chemical reactions within the DAC unit (e.g., of sorbents, tubes, lubricants) that might release contaminants?
2 Does the DAC unit, in addition to CO_2, also concentrate other (trace) gases present in the ambient air?

When damage is caused by toxic components in the CO_2 stream — such as nitrogen oxides or ethene — two types of damage are distinguished. **Acute damage** results from **short-term exposure** (hours to days) at high concentrations, is usually visible, and appears soon after exposure. **Chronic damage** results from **long-term exposure** to lower concentrations, often leading to reduced growth, lower productivity, and diminished quality.

At the plant level, **threshold limit values (TLVs)** are known for certain compounds. A TLV represents the concentration above which plants are at risk of damage, and below which no significant risk is expected. For many substances, no specific TLV has been established; however, their chemical structure often provides clues about potential phytotoxicity. The table below summarizes known phytotoxic classes with a general risk assessment, along with specific TLVs where available.

Class and compound	Risk	TLV
Aliphatic hydrocarbon: Alkanes	Saturated hydrocarbons, relatively unreactive. Low risk.	
Aliphatic hydrocarbon: Alkenes	Unsaturated due to presence of double c-bond, makes them more reactive. Average to high risk.	Ethene: 11 ppb (8 hours); 5 ppb (4 weeks)[10]
Aromatic hydrocarbon	Unsaturated, but less reactive than alkenes. Might be a risk at high concentrations.	Benzene: >650 ppb (weeks)[11]
Oxidated hydrocarbons	Due to O better soluble in water compared to hydrocarbons. Low risk with high TLVs.	Acetone: 25 ppm[12]
(Organic) halogens	Halogens are highly reactive. Average to high risk.	Trichloroethylene: 2 ppb[12]
Nitrogen compounds: Nitrogen oxides (NO_x) and ammonia	Highly reactive. High risk.	NO_x: 40 ppb (24-hours); 16 ppb (year)[13] NH_3: 144 ppb (year)[14]
Sulphur compounds	Reactivity different per compound. Low to high risk.	H_2S: 176-949 ppb (day); 10-88 ppb (year)[15]

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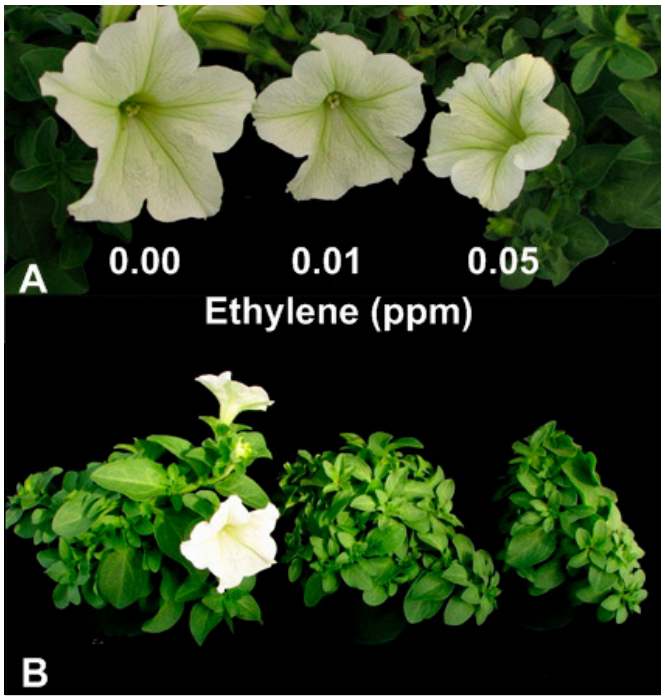
The listed TLVs refer to concentrations in greenhouse air. If a CO_2 stream contains a potentially harmful compound, it doesn't necessarily pose an immediate risk, as it will typically be diluted upon introduction into the greenhouse. However, it does require careful consideration and monitoring to understand what actually happens in practice.

Growers and DAC suppliers can use the overview as a starting point to **discuss CO_2 quality and potential guarantees** around gas purity. A few key considerations:

- The degree to which a greenhouse is "closed" determines ventilation and the risk of phytotoxic gas accumulation. **Less ventilation (especially in winter) increases risk**. Identify when and how long the greenhouse is typically closed — extra monitoring during these periods may be needed.
- Unlike human health standards (e.g., ACGIH/OSHA), there is **no global TLV table for plants**. Not all phytotoxic gases or their threshold levels are fully understood. If crop issues arise, consider a **broad-spectrum gas analysis** focused on the compound classes listed in the overview.
- Some gases are harmful even at extremely low concentrations! If a DAC supplier has already conducted gas analyses, always check the detection limits used — a compound may go unnoticed if levels fall below the equipment's sensitivity.

Please note: Work is underway to update the overview of phytotoxic classes, compounds, and TLVs, as well as to enhance our greenhouse modeling software (KASPRO) to calculate the dilution of contaminants in CO_2 streams. For example, if gas analysis shows that a DAC unit's CO_2 contains traces of a nitrogen compound, the model can assess how this compound dilutes in a closed tomato greenhouse and identify when the risk to crops is highest during the year. This calculation can be performed for any contaminant, provided that the value in g gas/kg CO_2 and CO_2 dosing are specified. Such insights help suppliers decide whether additional filtration is necessary before offering their machines to growers.



Effects of low concentration ethene (ethylene) on petunia. After several weeks of exposure, flower size (A) and internode elongation (B) are reduced at 0.01 and 0.05 ppm compared with control (0.00 ppm ethene). Source: R. Leatherwood and N. S. Mattson, Cornell University.

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CO_2 Storage

CO_2 storage can play a crucial role in making Direct Air Capture (DAC) economically viable for greenhouse applications. DAC systems typically operate at a nearly constant production rate throughout the day, whereas CO_2 demand in greenhouses varies significantly — it is usually zero at night and peaks during sunny hours with high ventilation rates.

Because DAC capacity is currently more expensive than storage capacity, it can be economical to minimize DAC size and use storage to balance supply and demand. Storage allows CO_2 captured at any time to be used later, ensuring high machine utilization and the flexibility to operate when energy prices are lowest. This approach enables growers to meet daytime or even seasonal peaks without oversizing the DAC unit.

There are several possible technologies for CO_2 storage, each with different cost and technical characteristics. Options include storing CO_2 in large, unpressurized balloons; as compressed gas in pressurized tanks; chemically bound in solvents; or as liquid CO_2 in storage tanks. The most (cost-) effective solution depends strongly on the specific situation at the grower as well as on the concentration of CO_2 that the DAC machine can deliver.

For instance, if the DAC system produces CO_2 with a purity below 90%, liquefying it for long-term or seasonal storage may be technically impractical or too expensive. However, a smaller day–night buffer using compressed gas storage may still be a feasible and economical option if sufficient space is available.

WUR is currently running a project together with TNO to model and evaluate these types of scenarios. The goal is to provide insight into which CO_2 storage solutions are most feasible and cost-effective for horticultural applications. The project is financed by Kas als Energiebron, a collaboration between the Ministry of Agriculture, Fisheries, Food Security and Nature, and Glastuinbouw Nederland.

Impression of CO_2 storage options. Source: ChatGPT

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Welcome Greenhouse Growers!

This publication is made with you — the greenhouse grower — in mind. With new CO_2 technologies like Direct Air Capture (DAC) entering the scene, we've noticed that many suppliers from outside horticulture aren't fully familiar with how CO_2 is actually used in greenhouses — how much is needed, when it's dosed, and what typical concentration levels are.

Growers and CO_2 suppliers often speak in different terms. For example, you might express your CO_2 demand in kilograms per hour per hectare, while a supplier talks about production in kilograms per 24 hours. That's why we created this document: to provide practical numbers, explain key concepts, and help you better understand what DAC might offer — and what to ask if a supplier approaches you.

In the navigation menu you can find an overview of the topics discussed in this document, or simply use the arrow buttons you see below.

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CO_2 Properties

Carbon dioxide (CO_2) is a gas that's naturally present in the atmosphere and is also emitted by human activities like burning coal, oil, and gas. CO_2 is widely used in various sectors as a resource: in greenhouse horticulture to boost crop growth, in the food and beverage industry for carbonating drinks and preserving packaging, in fire extinguishers as a suppressant, and even in water treatment. Yet, CO_2 is also a major greenhouse gas—trapping heat in the atmosphere and driving climate change. This makes it both a valuable resource and a critical environmental concern. However, the properties of CO_2 are constant, and having them at hand can be useful for making simple estimations or discussing various scenarios.

Several online tools, such as the NIST Chemistry WebBook, are available to view and calculate properties of CO_2.

- Chemical formula: CO_2
- Appearance: Colourless as a gas and liquid, white as a solid.
- Odour: At low concentrations it is odourless, but at high concentrations it has a sharp acidic smell.
- Flammability: Non-flammable
- Solubility: Carbon dioxide is soluble in water in which it reversibly forms carbonic acid (H_2CO_3).
- Molecular weight: **44.01 g/mol**
- Density – Gas: CO_2 is about 1.5 times heavier than air. In gaseous state at 20 °C and 1 atm (NTP) CO_2 has a density of **1.84 kg/m³**. Reversely, 1 kg of CO_2 occupies a volume of about **0.54 m³**.
- Density - Liquid: CO_2 only exists as a liquid within a temperature range of -56.6°C and 31°C and pressures between 5.2 bar and 74 bar. Fully saturated at –37 °C and 11 bar, liquid CO_2 has a density of **1100 kg/m³**.
- Density - Solid: Solid CO_2 is also referred to as "dry ice" and forms at atmospheric pressure below the boiling point of -78.5 °C. It has a density of **1560 kg/m³**.
- Boiling point: At atmospheric pressure solid CO_2 sublimes at -78.5 °C, meaning that it passes directly from solid to gaseous state.
- Critical temperature: 31 °C
- Critical pressure: 74 bar
- Triple-point temperature: -56.6°C
- Triple-point pressure: 5.2 bar

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Direct Air Capture – What is it?

Direct Air Capture (DAC) is a technology that **removes CO_2 directly from the ambient air** — not from chimneys or industrial emissions, but from the same air that surrounds us all. The captured CO_2 can either be permanently stored (CCS) or reused (CCU). One potential reuse application is dosing the CO_2 in greenhouses to boost plant growth.

Though there are many technologies under development (see section Direct Air Capture – Technologies) a recent report Direct Air Capture: Definition and Company Analysis by the U.S. Department of Energy found that the majority of DAC companies use a solid sorbent as their CO_2 capture medium.[16] Sorbents are materials that chemically or physically bind CO_2. Figure 12 shows how this type of DAC system typically works.

The machine first pulls in ambient air (≈425 ppm) using fans, bringing it into contact with the sorbent to capture CO_2. The treated air leaving the machine now contains less CO_2 (<425 ppm). Next, the captured CO_2 is released in concentrated form. Energy is required for the regeneration process, and most companies achieve this through heating, or a combination of heating and vacuum, applied to the sorbent. Depending on its concentration, the captured CO_2 can either be supplied directly to greenhouses or stored for later use when demand arises.

Importantly, DAC is not a single technology: different systems use different capture and regeneration methods, and vary in how they deliver the CO_2. Some operate in batches, others continuously. We have come across systems that focus on

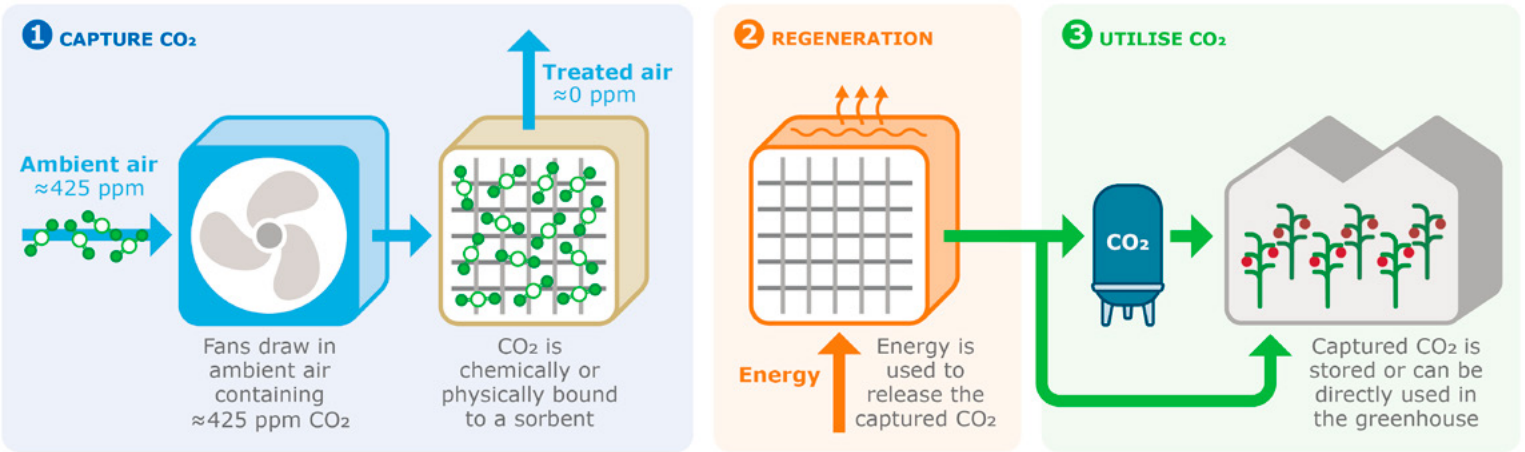

Figure 12: General working principle of a DAC concept that captures CO_2 from air using a sorbent.

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producing highly concentrated CO_2 (up to nearly pure), while others produce a stream of lower-concentration CO_2. These differences matter — especially in a greenhouse context. The company analysis by the U.S. Department of Energy further reports that 142 companies are currently developing DAC. Of these, 121 focus on "CO_2-concentrating DAC," which is likely the most relevant for applications such as horticulture. Geographically, 81 companies are based in North America, with most of the remainder clustered in Western Europe.[16]

Within the IDC CO_2 project, we aim to test DAC systems and assess how well different setups fit with horticultural use. For example, tomatoes and gerbera have different CO_2 needs and patterns — one DAC system may work well for one crop, but not for another. While DAC offers a potentially clean and local CO_2 source, it's important for growers to understand what a specific system delivers, how it fits into their operations, and what the cost implications are.

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Direct Air Capture – Technologies

Direct Air Capture (DAC) can be achieved using various technologies, each with its own characteristics. Figure 13 summarizes the DAC approaches identified in a recent literature review.[17]

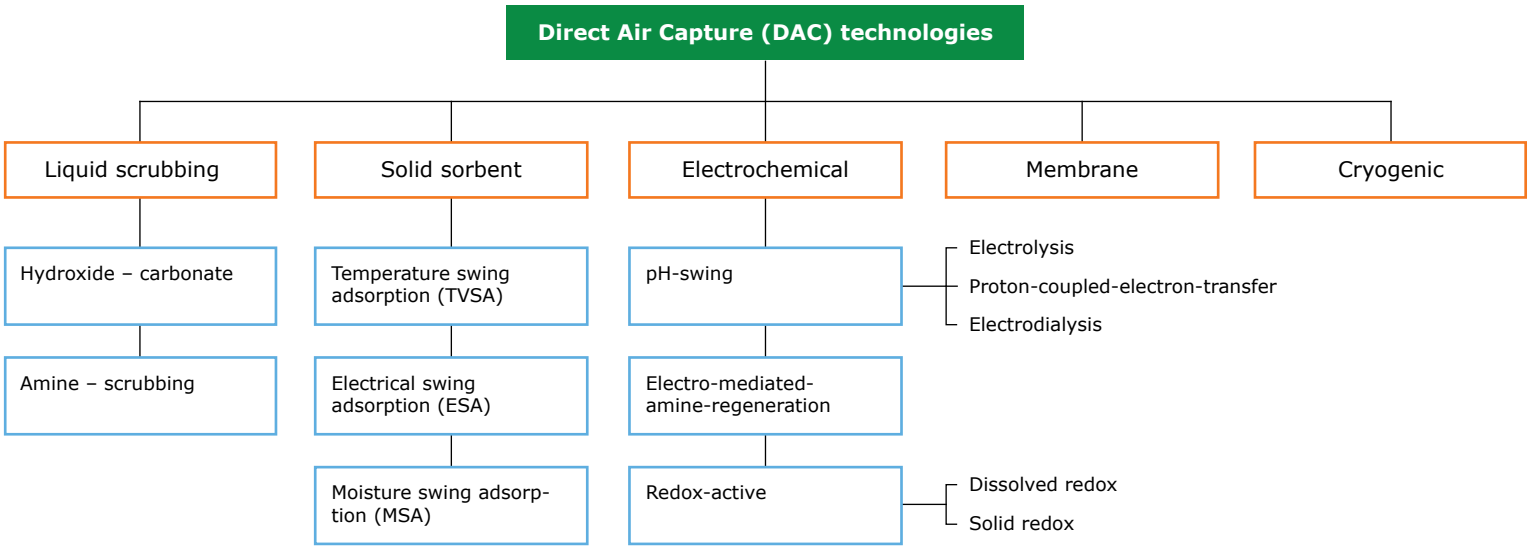

Figure 13: Overview of DAC technologies. Source: Adapted from Bouaboula et al. (2024).[17]

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To put these technologies into context, we can look at the U.S. Department of Energy's recent report Direct Air Capture: Definition and Company Analysis. The report identifies **142 companies worldwide** currently developing DAC systems. Roughly two-thirds use **solid sorbents** as the capture medium, while about one-quarter rely on **liquid solvents**. The remainder pursue novel approaches such as membranes or cryogenic separation (see Figure 14).

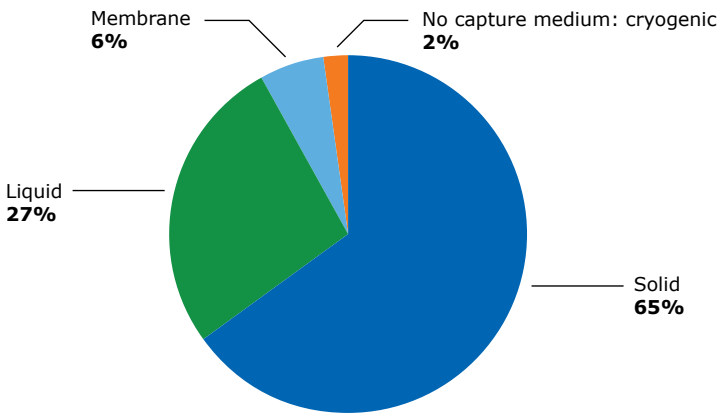

Figure 14: Types of capture media used by DAC companies.
Source: Adapted from Faber (2025).[16]

Most companies regenerate their capture media through some combination of temperature swings, vacuum, or electrochemical processes, with a smaller number exploring alternative methods involving moisture, chemical reactions, or plasma (see Figure 15). More elaborate information is available in the report Direct Air Capture: Definition and Company Analysis.[16]

Which technologies and implementation designs will ultimately provide the most cost-effective solutions for horticultural applications remains uncertain. This will also depend on whether clusters of greenhouses adopt a **centralised DAC hub** with a shared distribution network or rely on **stand-alone units** operated by individual greenhouse companies. Some systems, like liquid scrubbing with solvents, require (very) high temperatures and operate best at large industrial scale. These could be more suited for centralised DAC facilities that capture CO_2 and then distribute it to growers. In contrast, solid sorbent–based DAC systems use materials that bind CO_2 at lower temperatures and are typically modular. This makes them more promising for on-site use at greenhouse locations, offering a local CO_2 supply. The IDC CO_2 project will track ongoing developments, test DAC systems, and evaluate how well different configurations meet the needs of horticulture.

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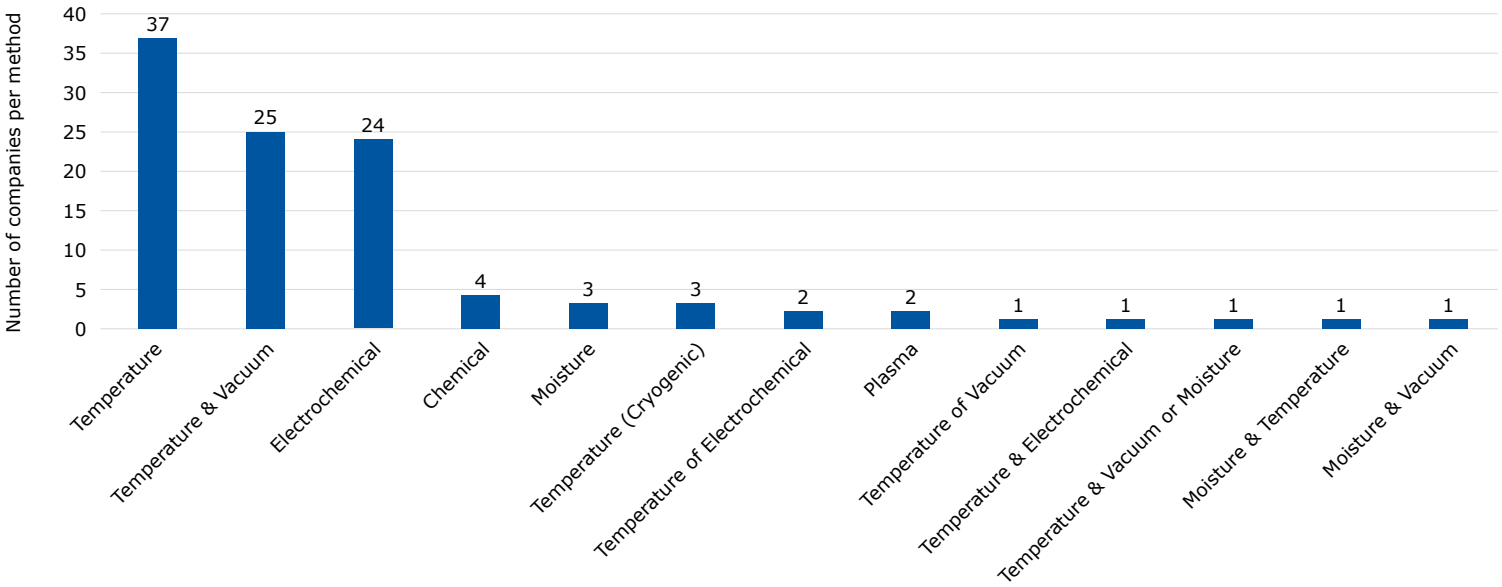

Figure 15: Regeneration methods used by DAC companies. Source: Adapted from Faber (2025).[16]

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CO_2 Metrics In Horticulture

CO_2 concentration

- **ppm (parts per million)** CO_2 concentrations in air are usually expressed as ppm. For instance, present atmospheric CO_2 concentration is around **425 ppm**. In greenhouses, growers often aim for higher CO_2 concentrations—**up to 1200 ppm**—depending on the crop.
- **% (percentage by volume)** CO_2 supplied by industry is usually expressed as a percentage of the total volume of the gas mixture. Currently, greenhouses use CO_2 from:
  - Flue gases of CHP : 5-6% (=50,000-60,000 ppm)[18]
  - OCAP: 98-100% (=980,000-1,000,000 ppm)
  - Pure, liquified CO_2: 99-100% (=990,000-1,000,000 ppm)

Why does concentration matter?
In principle, greenhouses can use any CO_2 concentration above the desired indoor level. **However, the concentration of the CO_2 supply strongly influences the required gas volume**. For example, raising the CO_2 level in a greenhouse using a gas flow containing only 1,000 ppm CO_2 requires significantly more volume than using a stream of pure CO_2. The inverse relationship between CO_2 concentration and required volume has two key implications:

1 **Low-concentration CO_2 is generally unsuitable for storage**, because the large volumes required make it impractical and/or cost-prohibitive. DAC systems that (only) produce low-concentration CO_2 must therefore supply CO_2 in sync with real-time CO_2 demand of a greenhouse. CO_2 demand in greenhouses mainly occurs during the light period. In the Netherlands, many growers use artificial lighting, which extends the period of CO_2 demand, though night-time demand remains minimal. Also see the section on CO2 Storage.

2 **Dosing low-concentration CO_2 requires large gas volumes**, and if the supplied gas mixture is colder or warmer than the greenhouse air, this may affect the greenhouse climate and increase a grower's overall energy costs.

The optimal CO_2 concentration for a DAC system to produce is a cost-benefit trade-off, influenced by real-time CO_2 demand, achievable production capacity, purification and storage costs, and any additional energy use.

CO_2 dosing

CO_2 dosing refers to the amount of CO_2 introduced into the greenhouse per unit of time and area. It is usually expressed in **kilogram per hectare greenhouse per hour (kg/ha/h)** and typically ranges from **25 to 250 kg/ha/h**. On an annual basis the dosed CO_2 is often expressed as kg per m^2 greenhouse ($kg/m^2/y$).

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CO_2 Use per Crop

The CO_2 uptake by photosynthesis is usually expressed as **grams per m² greenhouse per hour (g/m²/h)** and can reach up to **7 g/m²/h**, or **70 kg/ha/h**. CO_2 uptake rates depend on crop type, light- and CO_2-levels. More information can be found in the section CO_2 Use Per Crop.

Why do growers dose more CO_2 than what the crop takes up?

Growers generally need to supply (much) more CO_2 than the crop actually absorbs. This is because greenhouses aren't airtight – CO_2 escapes through leaks. Vents are also opened intentionally to regulate temperature or humidity. More information can be found in the section Efficiency – CO_2 Crop Uptake Versus CO_2 Dosing.

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Key Aspects of DAC & Horticulture

The list below outlines key aspects of DAC technology and greenhouse horticulture to support technical discussions on feasibility and suitability. It can also serve as a questionnaire to help clarify expectations, technical requirements, and assess the potential match between CO_2 supply and demand.

DAC parameters	Units	Why is it important?
Total energy use *Electricity use *Heat use	kW_h/kg CO_2 kWh_e/kg CO_2 kWh_t/kg CO_2	Major influence on OPEX and therefore the cost per kg of CO_2 for the grower. Some growers have access to geothermal wells or heat grids, making the type of energy that a DAC system requires an important consideration.
Required power connection	single-phase or three-phase? Voltage (V) Amperage (A)	Provides an indication for required grid capacity. (At the time of publication, grid capacity is an issue in some parts of the Netherlands.)
Required heating capacity	kW	Indicates the required heating infrastructure and the potential to integrate with existing greenhouse heating systems. If the DAC system can use hot water, it's useful to note that Dutch growers typically have different supply temperatures depending on the source: around 40 °C with a heat pump, up to 70 °C with a CHP or boiler, and around 80 °C with geothermal. The return temperature from the DAC system helps determine whether the residual heat can still be used effectively within greenhouse operations.
Required heating temperature and return temperature	°C	
Required cooling capacity	kW	Some growers have cooling capacity available.
Desired cooling temperature and return temperature	°C	
Production capacity per machine or module	kg/h	Gives growers a general idea of how many machines they need for their cultivation, and indicates potential CO_2 storage size.
CO_2 concentration	ppmv or % vol.	Provides insight into required dosing volumes and whether CO_2 can be produced and stored during periods of low or no demand—potentially reducing costs when energy prices are low. In some cases, even seasonal storage may be a viable option.

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DAC parameters	Units	Why is it important?
Volume output	m^3/hour	The volume of CO_2 or gas mixture produced influences the type and size of piping required for transport and dosing within the greenhouse.
Pressure	bar	Depending on the pressure, different CO_2 dosing systems may be more appropriate or effective.
CO_2 temperature	°C	Growers typically allow some temperature variation, but if the CO_2 supply differs significantly from the greenhouse temperature, it may affect the crop or disrupt climate control systems—especially when large volumes are dosed.
Moisture content	g/m^3	May cause condensation (linked to dew point temperature), which can promote fungal diseases in the greenhouse. Excess moisture can also disrupt climate control. This is especially important when large volumes of CO_2 are dosed, as is more often the case with low-concentration CO_2.
Mode of operation Startup and shutdown time	Continuous or batch? minutes	The mode of operation affects integration with the greenhouse CO_2 demand profile. Under mid to high light conditions and closed vents, a fully grown crop can deplete the CO_2 inside a greenhouse in a matter of 30 minutes! A short startup and shutdown time makes for easy and flexible control.
Dimensions	Length, width and height (m)	Limited available space can be a constraint for some growers, and local building regulations—such as height restrictions—should also be taken into account.
Weight	kg/m^2	Indicates whether additional foundation work is required, which may lead to extra costs.
Intake air quality	N/A	While DAC systems typically include air filters, local air quality can still influence performance. Factors such as proximity to industrial areas, highways, and the presence of dust or pollen can affect filter load and maintenance needs.
Other outputs	N/A	Are there any by-products besides CO_2 that growers should be aware of, such as wastewater, other gases, or hazardous waste materials?
Maintenance	N/A	What maintenance is required and what are the costs? Especially the life expectancy of the sorbent or solvent is key.

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Greenhouse parameters	Units	Why is it important?
Energy sources	N/A	Depending on the available energy sources, a DAC supplier may adapt their system to use them efficiently. Sustainable options a grower may have access to include geothermal energy, heat grids, heat pumps, thermal energy storage, solar panels, and wind turbines.
Available temperature heating water	°C	Indicates whether the existing heating water can be used directly or requires upgrading to a higher temperature to meet the DAC system's requirements.
CO_2 demand	kg/ha/h or kg/h	Ultimately, the hourly CO_2 demand data of a greenhouse offers the most valuable insights into how to best align CO_2 supply from a DAC system with the greenhouse's actual needs.
Target and achieved CO_2 levels	ppm	Shows what a grower is aiming for and if they realise their target.
Climate computer	N/A	The type of climate control system and software provider may be relevant for the DAC supplier to ensure seamless integration and control.

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Efficiency - CO_2 Dosing Versus CO_2 Crop Uptake

CO_2 Crop Uptake

CO_2 uptake by crops can vary widely, depending not only on the crop species but also on growing conditions such as light intensity, how much light the crop can intercept, and the CO_2 concentration in the greenhouse.

For example, cucumber can absorb around 7 g CO_2/m²/h under high light conditions (1000 µmol/m²/s PAR) and high CO_2 levels (≥ 700 ppm). Under lower light (500 µmol/m²/s PAR) but the same CO_2 level, this drops to about 4 g CO_2/m²/h.[8]

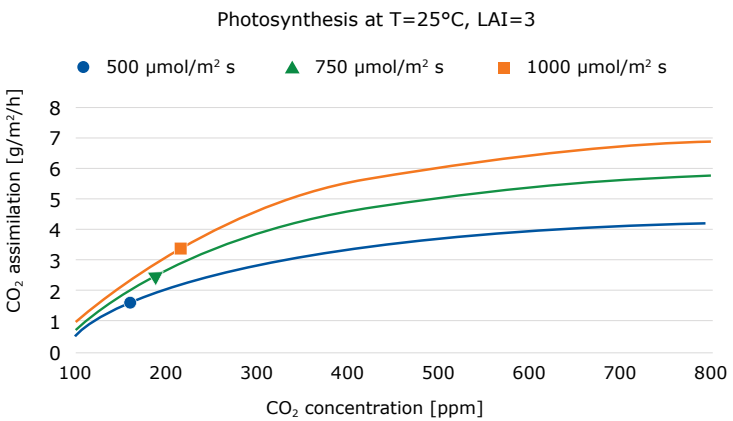

Figure 8: Net photosynthesis (g/m²/h) of cucumber at various light levels and CO_2 concentrations. Source: Adapted from Hogewoning (2024).[8]

Figure 8 shows the CO_2 assimilation (also known as the photosynthesis curve) for cucumber under various light and CO_2 levels. It's clear that photosynthesis generally increases with higher CO_2 concentrations. However, the relationship is not linear — there is a limit to how much extra CO_2 a crop can use. So, while increasing CO_2 can boost yield, the benefits level off at higher concentrations.

Keep in mind that cucumber has a relatively high light use efficiency (LUE). In other words, it converts light and CO_2 into growth more effectively than many other crops. In contrast, LUE can be much lower in other species, particularly in some floricultural crops, where maximum photosynthesis rates can be less than half of those observed in cucumber.[9]

CO_2 dosing

In theory, if CO_2 dosing were matched exactly to crop uptake, there would be no losses—every molecule of CO_2 would be assimilated by the plants. However, this assumes a perfectly sealed greenhouse, which is not the case in practice.

In reality, greenhouses experience continuous CO_2 losses due to:

- Infiltration (leakage): typically around 5,000 to 10,000 m³/ha/h, depending on construction quality, size, and wind conditions.
- Intentional ventilation: used to regulate temperature and humidity, which also releases CO_2 into the outside air. Depending on vent opening and wind speed, ventilation rates can go up to 60,000 m³/ha/h.

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As a result, the more ventilation occurs, the lower the efficiency of CO_2 dosing—since a larger portion of the supplied CO_2 escapes before it can be used by the crop.

Efficiency

Figures 9 through 11 show the CO_2 uptake by a tomato crop in a high-tech, semi-closed Dutch greenhouse compared to CO_2 losses through ventilation. Three scenarios are illustrated:

maintaining the greenhouse at the ambient outdoor concentration of 425 ppm, and increasing the target concentration to 600 ppm and 800 ppm.

Figure 9 shows that maintaining the greenhouse CO_2 concentration at the outdoor level (425 ppm) requires approximately 60 tons/ha/y, with minimal losses to the outside. Yield reaches 67 kg/m^2 per year. Efficiency is defined as the percentage of the dosed CO_2 that is assimilated by the crop.

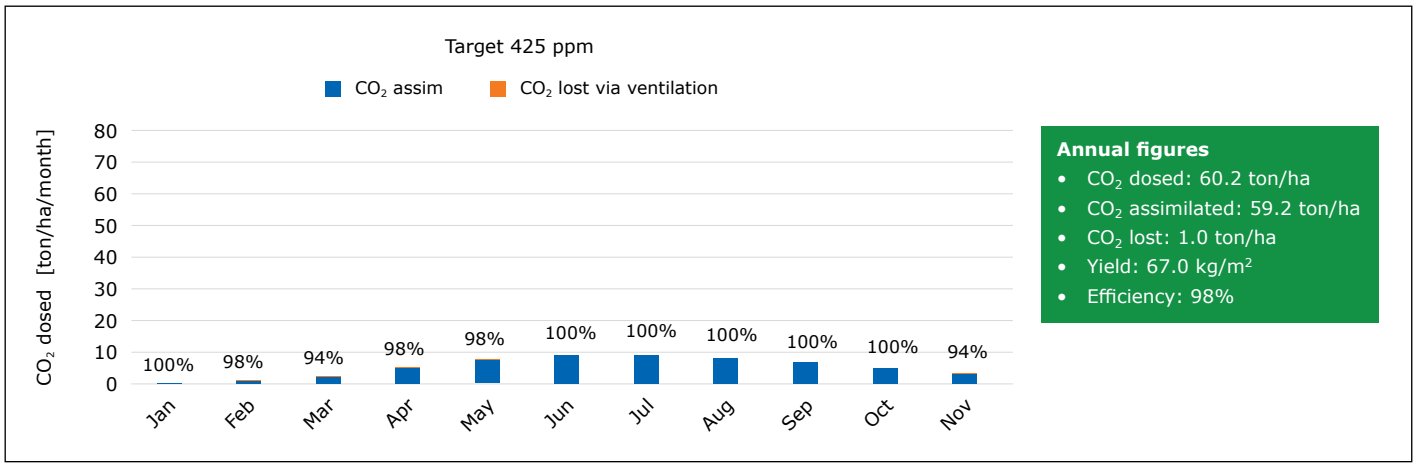

Figure 9: Maintaining the greenhouse CO_2 concentration at the outdoor level (425 ppm) requires approximately 60 tons/ha/y, with minimal losses to the outside. Efficiency is defined as the percentage of the dosed CO_2 that is assimilated by the crop.

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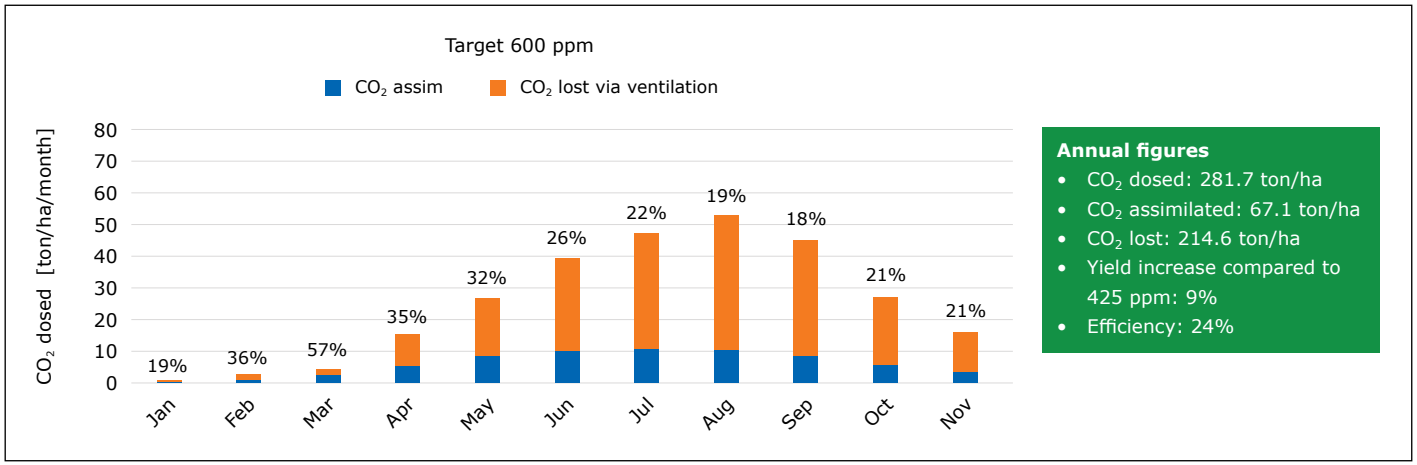

Figure 10: Raising the CO_2 target concentration to 600 ppm, requires much more CO_2 compared to maintaining 425 ppm. Dosing efficiency drops to 24%, but yield increases by 9% compared to 425 ppm due to higher CO_2 assimilation by the crop.

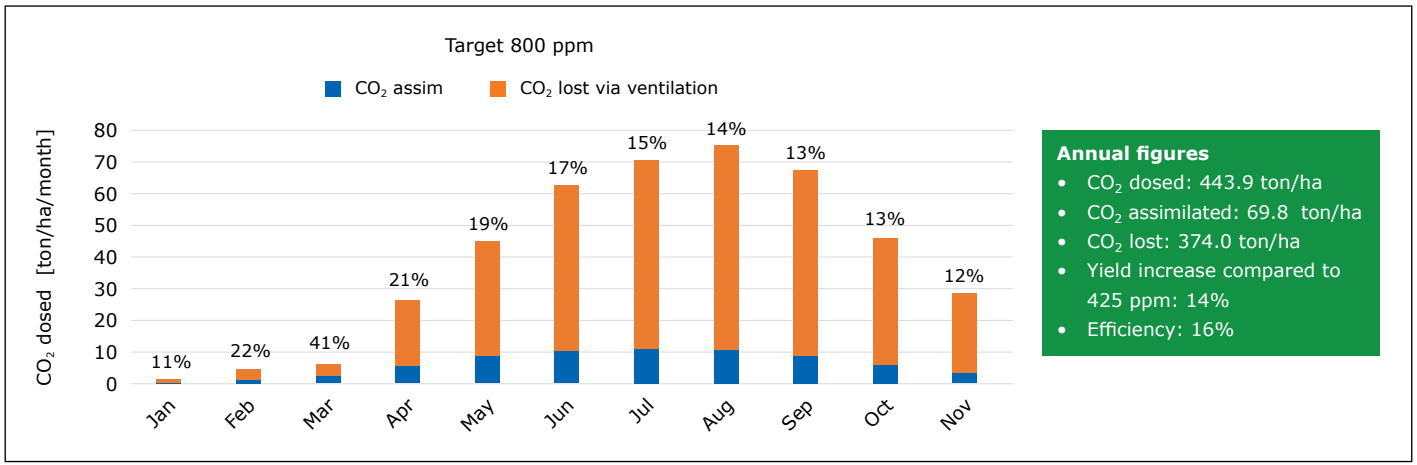

Figure 11: At a target of 800 ppm, dosing efficiency drops to 16%, while yield increases by 14% compared to 425 ppm. However, the yield gain from increasing CO_2 from 600 to 800 ppm is smaller than the gain from 425 to 600 ppm. This reflects the non-linear response of photosynthesis to CO_2: the curve levels off, meaning additional CO_2 results in diminishing returns in crop growth (see Figure 8).

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CO_2 Quality

While CO_2 is essential for plant growth, certain gases—known as phytotoxic gases—can harm plants even at very low concentrations. For DAC suppliers targeting the greenhouse sector, it's important to ask: "**Can I guarantee that my system does not emit by-product gases that could harm plants or humans?**" Two potential sources to consider:

1 Could the system's processes (e.g., heating, cooling, vacuum) cause material degradation or chemical reactions within the DAC unit (e.g., of sorbents, tubes, lubricants) that might release contaminants?
2 Does the DAC unit, in addition to CO_2, also concentrate other (trace) gases present in the ambient air?

When damage is caused by toxic components in the CO_2 stream — such as nitrogen oxides or ethene — two types of damage are distinguished. **Acute damage** results from **short-term exposure** (hours to days) at high concentrations, is usually visible, and appears soon after exposure. **Chronic damage** results from **long-term exposure** to lower concentrations, often leading to reduced growth, lower productivity, and diminished quality.

At the plant level, **threshold limit values (TLVs)** are known for certain compounds. A TLV represents the concentration above which plants are at risk of damage, and below which no significant risk is expected. For many substances, no specific TLV has been established; however, their chemical structure often provides clues about potential phytotoxicity. The table below summarizes known phytotoxic classes with a general risk assessment, along with specific TLVs where available.

Class and compound	Risk	TLV
Aliphatic hydrocarbon: Alkanes	Saturated hydrocarbons, relatively unreactive. Low risk.	
Aliphatic hydrocarbon: Alkenes	Unsaturated due to presence of double c-bond, makes them more reactive. Average to high risk.	Ethene: 11 ppb (8 hours); 5 ppb (4 weeks)[10]
Aromatic hydrocarbon	Unsaturated, but less reactive than alkenes. Might be a risk at high concentrations.	Benzene: >650 ppb (weeks)[11]
Oxidated hydrocarbons	Due to O better soluble in water compared to hydrocarbons. Low risk with high TLVs.	Acetone: 25 ppm[12]
(Organic) halogens	Halogens are highly reactive. Average to high risk.	Trichloroethylene: 2 ppb[12]
Nitrogen compounds: Nitrogen oxides (NO_x) and ammonia	Highly reactive. High risk.	NO_x: 40 ppb (24-hours); 16 ppb (year)[13] NH_3: 144 ppb (year)[14]
Sulphur compounds	Reactivity different per compound. Low to high risk.	$H2_S$: 176-949 ppb (day); 10-88 ppb (year)[15]

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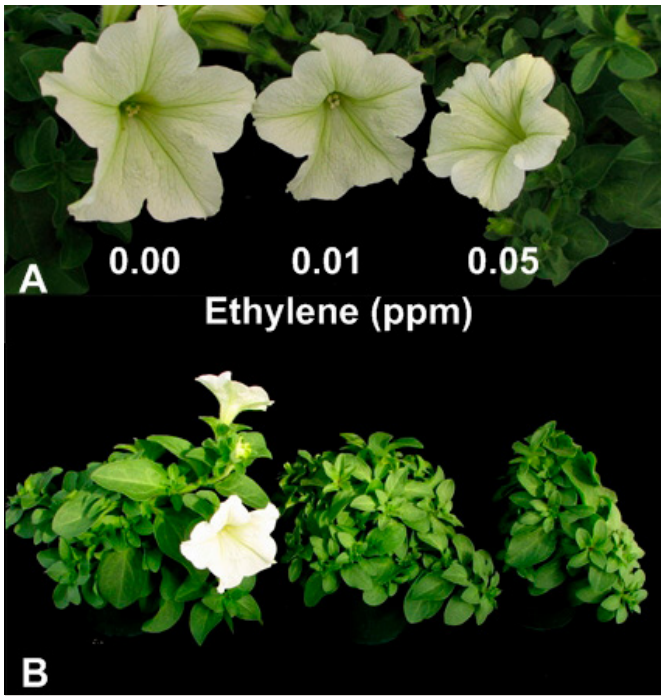
The listed TLVs refer to concentrations in greenhouse air. If a CO_2 stream contains a potentially harmful compound, it doesn't necessarily pose an immediate risk, as it will typically be diluted upon introduction into the greenhouse. However, it does require careful consideration and monitoring to understand what actually happens in practice.

Growers and DAC suppliers can use the overview as a starting point to **discuss CO_2 quality and potential guarantees** around gas purity. A few key considerations:

- The degree to which a greenhouse is "closed" determines ventilation and the risk of phytotoxic gas accumulation. **Less ventilation (especially in winter) increases risk**. Identify when and how long the greenhouse is typically closed — extra monitoring during these periods may be needed.
- Unlike human health standards (e.g., ACGIH/OSHA), there is **no global TLV table for plants**. Not all phytotoxic gases or their threshold levels are fully understood. If crop issues arise, consider a **broad-spectrum gas analysis** focused on the compound classes listed in the overview.
- Some gases are harmful even at extremely low concentrations! If a DAC supplier has already conducted gas analyses, always check the detection limits used — a compound may go unnoticed if levels fall below the equipment's sensitivity.

Please note: Work is underway to update the overview of phytotoxic classes, compounds, and TLVs, as well as to enhance our greenhouse modeling software (KASPRO) to calculate the dilution of contaminants in CO_2 streams. For example, if gas analysis shows that a DAC unit's CO_2 contains traces of a nitrogen compound, the model can assess how this compound dilutes in a closed tomato greenhouse and identify when the risk to crops is highest during the year. This calculation can be performed for any contaminant, provided that the value in g gas/kg CO_2 and CO_2 dosing are specified. Such insights help suppliers decide whether additional filtration is necessary before offering their machines to growers.



Effects of low concentration ethene (ethylene) on petunia. After several weeks of exposure, flower size (A) and internode elongation (B) are reduced at 0.01 and 0.05 ppm compared with control (0.00 ppm ethene). Source: R. Leatherwood and N. S. Mattson, Cornell University.

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CO_2 Storage

CO_2 storage can play a crucial role in making Direct Air Capture (DAC) economically viable for greenhouse applications. DAC systems typically operate at a nearly constant production rate throughout the day, whereas CO_2 demand in greenhouses varies significantly — it is usually zero at night and peaks during sunny hours with high ventilation rates.

Because DAC capacity is currently more expensive than storage capacity, it can be economical to minimize DAC size and use storage to balance supply and demand. Storage allows CO_2 captured at any time to be used later, ensuring high machine utilization and the flexibility to operate when energy prices are lowest. This approach enables growers to meet daytime or even seasonal peaks without oversizing the DAC unit.

There are several possible technologies for CO_2 storage, each with different cost and technical characteristics. Options include storing CO_2 in large, unpressurized balloons; as compressed gas in pressurized tanks; chemically bound in solvents; or as liquid CO_2 in storage tanks. The most (cost-) effective solution depends strongly on the specific situation at the grower as well as on the concentration of CO_2 that the DAC machine can deliver.

For instance, if the DAC system produces CO_2 with a purity below 90%, liquefying it for long-term or seasonal storage may be technically impractical or too expensive. However, a smaller day–night buffer using compressed gas storage may still be a feasible and economical option if sufficient space is available.

WUR is currently running a project together with TNO to model and evaluate these types of scenarios. The goal is to provide insight into which CO_2 storage solutions are most feasible and cost-effective for horticultural applications. The project is financed by Kas als Energiebron, a collaboration between the Ministry of Agriculture, Fisheries, Food Security and Nature, and Glastuinbouw Nederland.

Impression of CO_2 storage options. Source: ChatGPT

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CCS	carbon capture and storage
CCU	carbon capture and utilisation
CHP	combined heat and power
DAC	direct air capture
NTP	normal temperature and pressure
LUE	light use efficiency
TLV	threshold limit values
OCAP	organic CO_2 for assimilation of plants
PAR	photosynthetically active radiation

Abbreviations

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