



Guide to Production of

Greenhouse

Fruits and Vegetables

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Back Cover: Greenhouse pepper crop under supplemental lighting and energy curtains.

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Guide to Production of

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OVERVIEW

This book is Part B of a series that will replace Publication 836: *Growing Greenhouse Vegetables*. Visit ontario.ca/crops for more information.

This publication provides an overview of key concepts for the production of greenhouse fruits and vegetables in Ontario. This information is meant to be used as a guide for growers, and as part of the Greenhouse Vegetable Course. Crop-specific production guides will follow. For timely updates and more information on the Greenhouse Vegetable Course visit the ONGreenhouseVegetables.ca blog.

Maximizing fruit yield in a greenhouse operation requires proper management and control of the growing environment to achieve optimal plant growth. Greenhouse production is considered a type of controlled environment agriculture (CEA) because many factors can be controlled in today's high technology greenhouses. The factors discussed in this book include temperature,

irrigation, relative humidity, carbon dioxide (CO₂) and lighting.

Plant growth can be controlled by manipulating the environment of a greenhouse. However, it is recommended that a cost-benefit analysis be performed before implementing any changes to minimize input costs and waste while maximizing fruit yield and quality. For example, the costs and benefits of installing supplemental lighting must be weighed to ensure it is economically sustainable. This can be done by calculating and comparing the capital and operating costs versus the anticipated increases in production. Most greenhouse operators perform small-scale tests of new technologies in one section of their greenhouse before implementing it on a larger scale across their whole operation. Such tests should last for at least one growing season to collect enough data on input costs and yield and to be able to compare those numbers with previous seasons.



CHAPTER 1

Vegetative or Generative Plants

This chapter discusses some of the growth factors related to greenhouse production and how they influence vegetative and generative growth.

By adjusting light, temperature, water and nutrient regimes, producers can shift plants from a vegetative state to a generative state or vice versa to ensure a certain form or look of plant is obtained.

A **vegetative** plant produces more leaves than flowers and fruit. In this case, the plant has:

- large, thick, dark-green leaves and a thick stem with a light-green tinge at the growing point
- large, rough flowers on weak flower stems and trusses
- fruit that is small relative to the size of the plant
- extensive root growth

In contrast, a **generative** plant has:

- smaller leaves and a thin stem with a purple tinge at the growing point
- smaller, more numerous flowers that are prominently displayed
- fruit that is large compared to the size of the plant
- potentially poor fruit quality due to over-exposure to the sun

A plant that is well-balanced between the vegetative and generative growth is ideal ([Figure 1](#)).

Early in the planting cycle, plants tend to be vegetative. A plant grown at a low temperature and high humidity during early winter, when light levels are traditionally low, tends to be vegetative if it receives plenty of water and nutrition. By raising the temperature and decreasing the humidity and water, a more controlled plant may be obtained.

After the initial vegetative growth of vegetable crops, strategies should be implemented to obtain a generative plant that will provide fruit at the desired time. However, if plants become too generative, adjustments should be made to the growing strategies to encourage more vegetative growth. Further changes may be made to the way the plant grows by adjusting the day-night temperature differences.



Figure 1. (A) A balanced greenhouse tomato plant and (B) a vegetative greenhouse tomato plant.



CHAPTER 2

Temperature

Temperature influences several important processes that affect growth: photosynthesis and respiration, stomatal function, plant development and relative humidity.

Photosynthesis and Respiration

Photosynthesis is the process whereby plants use certain wavelengths of sunlight to convert CO_2 and water into sugars (carbohydrates) and oxygen. The plant then stores the carbohydrates, which serve as a source of energy. Sunlight between 400-700 nanometres (nm) in wavelength is considered the main **photosynthetically active radiation (PAR)** used most efficiently by plants for photosynthesis. Photosynthesis is affected by the amount of PAR that is available as well as CO_2 and water, the building blocks of carbohydrates.

Respiration is the process whereby carbohydrates produced by photosynthesis are broken down in the presence of oxygen to

produce energy (i.e., adenosine triphosphate (ATP)). This energy is then used in processes such as the initiation and development of roots, leaves, buds and fruit. Respiration can occur over a 24-hour period and is divided into cellular and photorespiration. While the processes involved in photorespiration are poorly understood, cellular respiration can be influenced by temperature.

The net result of photosynthesis and respiration is plant growth, which can be expressed as the accumulation of biomass. The optimum temperature to increase biomass depends on light intensity. As sunlight levels increase in the spring and summer, so should the temperature set point of the greenhouse. This will ensure the ratio of temperature to radiation (RTR) is ideal for balanced crop growth. The higher the light intensity, the higher the optimum temperature. During hours of sunshine, a higher temperature allows the plant to manufacture sugars and grow rapidly. At night, lower temperatures allow the sugars manufactured during the day to be translocated and stored in the growing points of the stem,

roots, leaves and fruit. This results in thicker and heavier plants. Regularly adjusting the temperature and determining when to make these adjustments will result in a well-balanced, highly productive crop. For most greenhouse crops, the optimum temperature is between 12–16°C during low light conditions and 15–25°C when light intensity is high.

Temperature Management

The optimum temperature for each crop depends on light conditions, the stage of growth and the season. By adjusting greenhouse temperatures, producers can control the rate of crop growth, its vigour, the shape or morphology of the plants, fruit size and, ultimately, yield. Generally, the optimum 24-hour temperature for lettuce is 17–18°C; tomatoes, 19°C; peppers, 19°C; and cucumbers, 21°C. However, in practice several temperature schemes have proven beneficial. [Figure 2](#) shows an example of the difference in temperature throughout the day on sunny and cloudy days. Sunny days typically require a higher temperature setting than cloudy days. Greenhouse operators manipulate temperature to develop the ideal plant with good form and high-quality production by maintaining an optimal 24-hour average. Temperature is usually raised in the afternoon to increase speed of growth and lowered in the early night to create a strong head, root and fruit base.

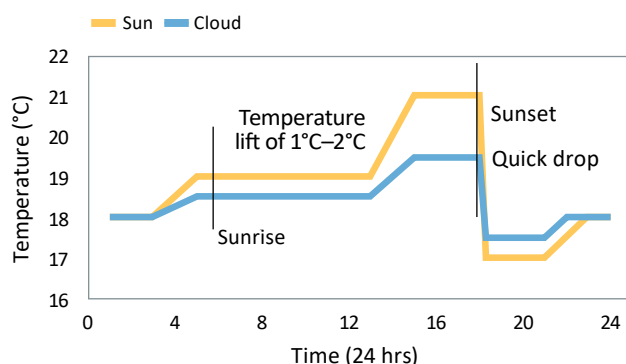


Figure 2. Typical greenhouse temperature profile for most vegetable crops on sunny and cloudy days.

Temperature and Plant Development

The development of leaves, flowers and roots requires energy provided by respiration which in turn, is influenced by temperature. For each degree increase between 10°C and 30°C, there is a corresponding 10% increase in leaf and flower initiation. The 24-hour average temperature determines not only the rate of crop development, but it also affects plant architecture. At a low 24-hour average temperature, the plant tends to have shorter internodes, thicker stems and leaves and large flowers. At a high 24-hour average temperature, the plant tends to have longer internodes, thinner stems and leaves and small, spindly flowers. The goal is to strike a balance between the two, since high 24-hour average temperatures weaken the plant and flowers, causing yield reduction, while low 24-hour temperatures delay harvest or damage flowers, resulting in malformed fruits.

Typically, the 24-hour average temperature is lower under low light conditions and higher under high light conditions. But greenhouse operators should also observe the morphological characteristics of the plant to determine how to adjust the greenhouse temperature. For example, cucumbers and lettuce have short, wide leaves when temperature at initiation is low, while at high temperatures, the leaves are long and narrow. The day-night temperature difference also affects the plant's shape. A small or zero day-night temperature difference results in more vegetative plants with short internodes and thicker, larger leaves; a large day-night temperature difference results in more generative plants with longer internodes and thinner, smaller leaves. During early plant development in the greenhouse, day temperatures should be kept close to night temperatures to encourage plant establishment. However, after the flowering and fruit-setting stages a day-night

temperature difference should be applied to produce a balanced plant.

Temperature and Relative Humidity (RH)

Temperature has an inverse relationship with relative humidity (RH). This means that when temperature increases, RH decreases. The opposite is also true: when temperature decreases, RH increases. Relative humidity also has an inverse effect on the transpiration rate and, therefore, on the water status of the plant. In general, plants grown at high RH have larger leaves and longer stems than those grown at a lower RH. There is more information about the relationship between temperature and RH in [Chapter 4, Relative Humidity](#).



Light

Light is electromagnetic radiation that acts as both a wave and a particle. Light particles (**photons**) move up and down like a wave. The length of the wave the light photon travels can be measured in nanometres (nm) and is known as the **wavelength**. Each wavelength is associated with a different energy and colour of light. Light quality refers to the “colour” of light defined by the wavelength that the photons are moving in. Energy and wavelength have an inverse relationship meaning that the longer the wavelength is, the less energy it has. Gamma rays have the shortest wavelength and highest level of energy, followed by X rays and ultraviolet (UV) light which have longer wavelengths and less energy. Most of the light that is used by plants for photosynthesis is known as **photosynthetically active radiation (PAR)** which is visible light to the human eye. The wavelength of PAR (400–700 nm) is longer than UV, but shorter than far-red (FR) and infrared radiation (IR) (heat) (Figure 3).

The intensity of a light source is usually measured in watts per square metre (W/m^2) or in micromoles per square metre per second ($\mu\text{mol}/\text{m}^2/\text{sec}$). UV, PAR, FR and IR light can be measured in W/m^2 but only PAR is measured in $\mu\text{mol}/\text{m}^2/\text{sec}$. The intensity of PAR is also known as **photosynthetic photon flux density (PPFD)**. Note that different equipment and control systems may use different units to measure light intensity. Table 1 shows the factors used to convert between different light units.

PAR is divided into three main wavelengths represented by their light colour as perceived by the human eye: blue light (400–500 nm), green/yellow/amber light (500–600 nm), and red light (600–700 nm). The quantity of these colours and the ratio of one colour to the other affects plant physiology (Figure 3B). Photosynthesis uses energy from PAR to combine water and CO_2 , producing sugars.

Greenhouses are designed and laid out to maximize the amount of light that comes in. This is beneficial in the winter months when sunlight levels are too low to support

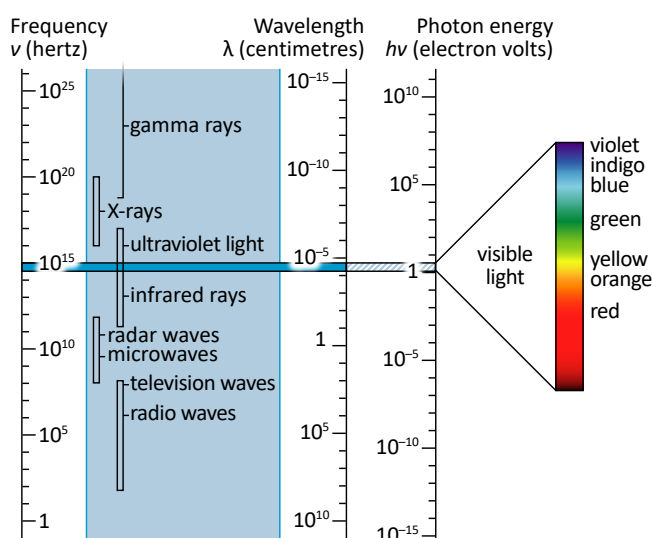


Figure 3A

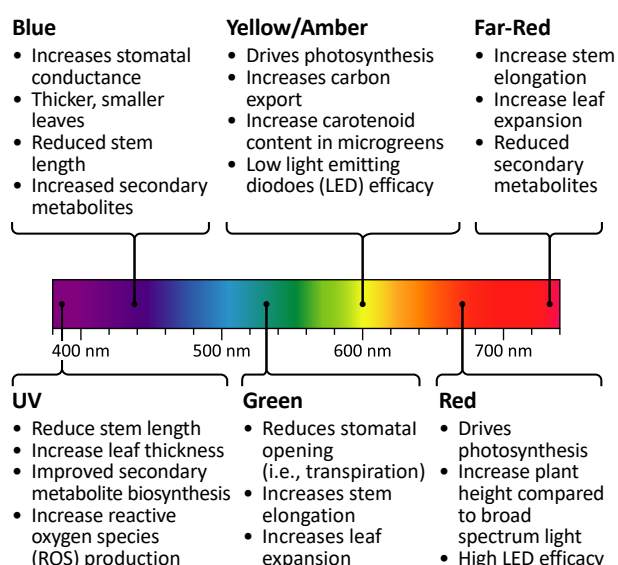


Figure 3B

Figure 3. (A) Wavelength and photon energy of different types of light along the light spectrum.

Source: Encyclopedia Britannica. (B) Impact of light quality on plant growth. Source: Agriculture and Agri-Food Canada.

Table 1. Conversion Table for Light

Light Source	W/m ² to $\mu\text{mol}/\text{m}^2/\text{sec}$	$\mu\text{mol}/\text{m}^2/\text{sec}$ to W/m ²	lux to $\mu\text{mol}/\text{m}^2/\text{sec}$	$\mu\text{mol}/\text{m}^2/\text{sec}$ to lux	lux to W/m ²
Sunlight	4.57	0.22	0.02	54.00	0.004
High-pressure sodium (SON/T)	4.98	0.20	0.01	82.00	0.002
Incandescent	5.00	0.20	0.02	50.00	0.004
High-pressure mercury	4.52	0.22	0.01	84.00	0.003
Metal halide	4.59	0.22	0.01	71.00	0.003

W/m² = watts/square metre

$\mu\text{mol}/\text{m}^2/\text{sec}$ = micromols/square metre/second

Source: Thimijan and Heins, 1985. HortScience 18: 818-822.

full production, but sometimes there is too much sunlight in the summer, resulting in high temperatures which are harmful to plants. Artificial supplemental lighting can be used to boost photosynthesis during the low light months. During the summer, shade curtains and greenhouse coatings can be used to decrease the light transmission and reduce heat load in the greenhouse. This section deals with natural light, but you can find more information on supplemental lighting in [Chapter 9, Supplemental Lighting for Winter Production](#).

Southwestern Ontario is the most southerly part of Canada. Therefore, it receives the most sunlight over the course of the year. Day length, sunshine hours, the amount of sunlight and energy are low in the early winter months, but increase in the spring and peak in the summer months, before decreasing in the autumn ([Figure 4](#)). With relatively little light energy available for growth in mid-winter, it often takes twice as long to get the same amount of growth in January as in May.

This must be considered when scheduling the production of greenhouse fruit and vegetable crops. Greenhouse management practices, including adjustments to seasonal and daily temperatures and nutrient levels, should be based on present light conditions.

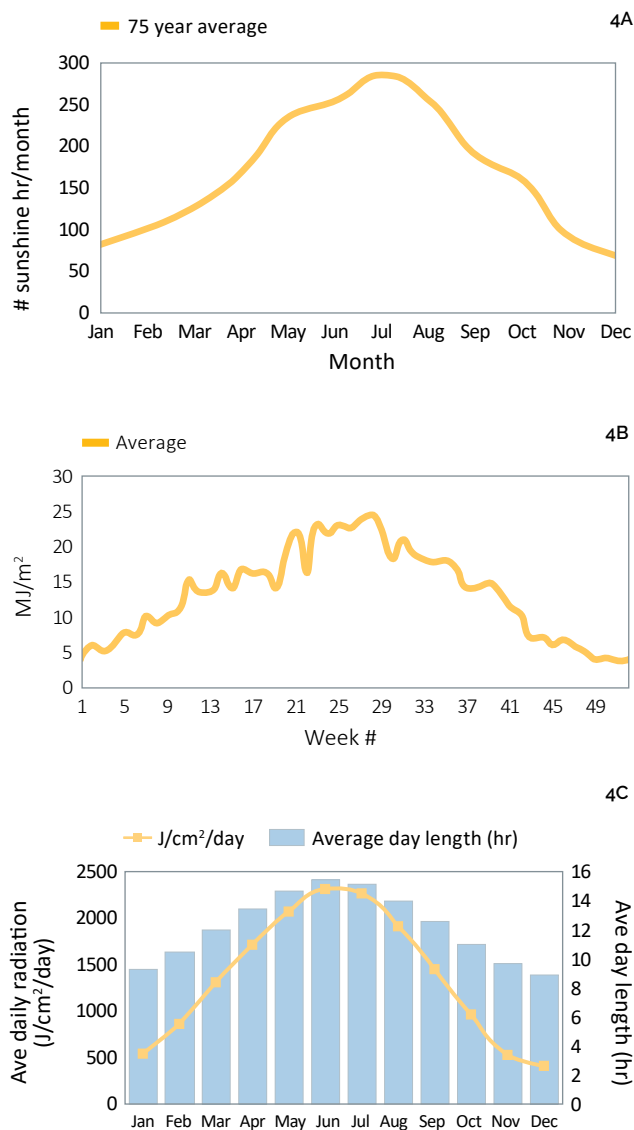


Figure 4. (A) Sunshine Hours — 75-Year Average (B) Global Radiation (measure of solar energy between 200 and 2,800 nm) — Weekly Average and (C) Global Radiation — 10-Year Average
Source: (A-B) Harrow Research and Development Centre, (C) Vineland Research and Development Centre.

The amount of light changes not only with the seasons but also with weather. For example, some cloudy days can have as little as 25% of the light as a sunny day. The quality of light can also differ between sunny and cloudy days depending on the type of clouds the light is shining through (Figure 5), (Figure 6).

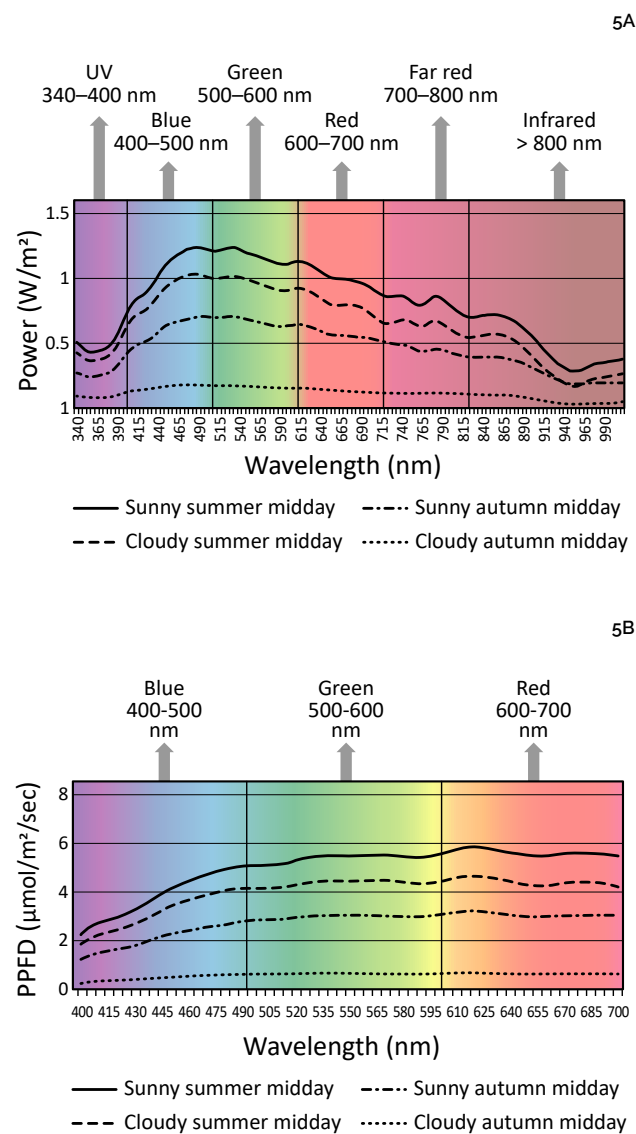


Figure 5. (A) Total light power and (B) PPFD representing light intensity and quality of outdoor sunlight in Windsor-Essex during midday on sunny and cloudy days in the summer and autumn of 2022.

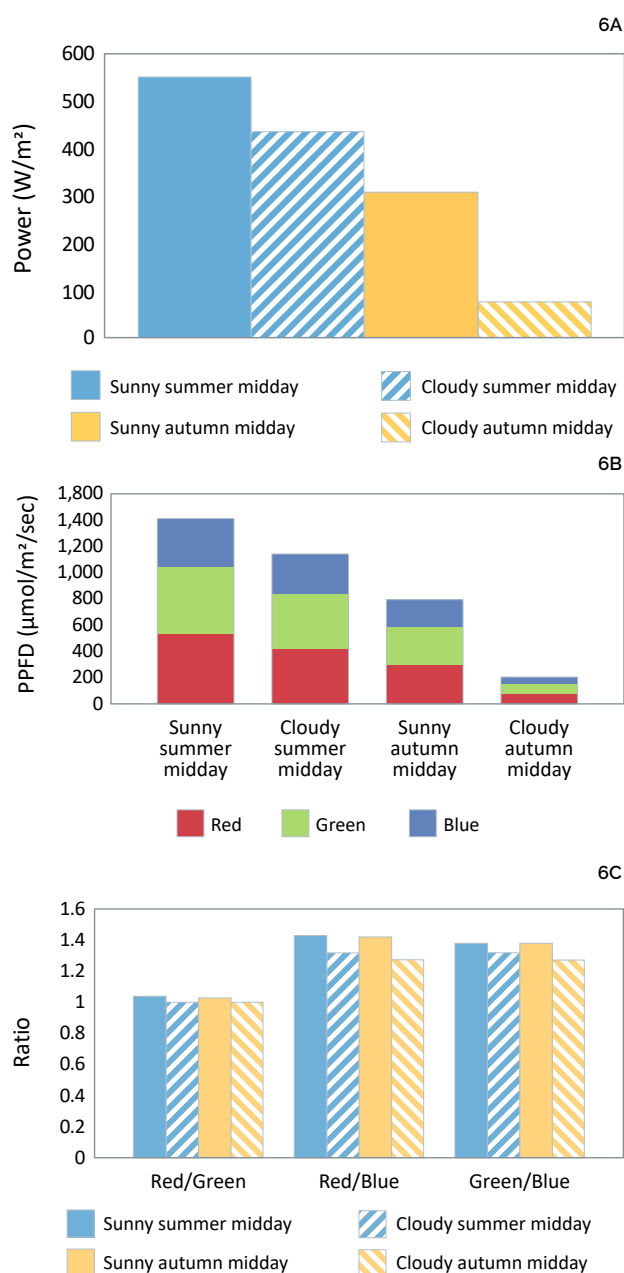


Figure 6. (A) Total power, (B) PPFD and (C) Light colours ratios representing light intensity and quality of outdoor sunlight in Windsor-Essex during midday on sunny and cloudy days in the summer and autumn of 2022.

Light Transmission and Distribution

Current roof designs and increased gutter height of greenhouses have improved light transmission, made management of the greenhouse environment easier and improved growing conditions (Figure 7). Glazing material greatly affects the lighting

environment in the greenhouse. Ontario greenhouses mainly use a single layer of glass or two layers of polyethylene (double poly) plastic as their cover material. Glass has a higher level of light transmissibility (it lets more light in) whereas double poly is better for heat retention. Double and triple poly combine energy conservation and low capital construction costs without loss of productivity.



Figure 7. (A) A modern greenhouse with higher gutter height and peak-roof profile. (B) An older-style greenhouse with low gutter height and rounded-roof profile.

When light shines on a surface it is reflected, absorbed and transmitted. The light reflection and absorption properties of a greenhouse glazing material determines how much light is transmitted through it. Theoretical calculations show that glass reflects about 4% of the light at each glazing/air interface. This means that the maximum light transmission for a single layer of material is about 92% (1 layer with 4% at each surface interchange = 8%). In contrast, the maximum theoretical transmission through a double layer of glass is 84% (2 layers with 4% at each surface interchange = 16%), indicating

the major loss of light is through reflection, not absorption. This explains why light transmission through a double layer of glazing material is considerably less than through a single layer of the same material with a total thickness equal to the double layer (Figure 8).

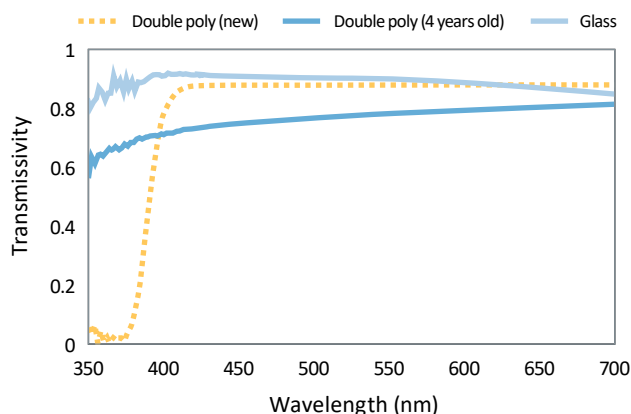


Figure 8. Comparison of light transmission between glass and double poly.

Unlike glass, there is a relatively small difference in light transmission between 100 and 150 micrometres (μm) poly films. In addition, research and development in additives for poly film production has increased the light transmission properties of the newer plastics, improving the quantity and quality of light reaching the plants. This has also allowed for adjustments of UV transmission to decrease disease incidence (since research shows that certain UV wavelengths increase the incidence of Botrytis) and allow bumblebees to perform in double poly greenhouses.

Keep in mind, however, that many conflicting reports have been published on the light transmission of different materials. Different measuring techniques usually account for these discrepancies. In general, only 50–75% of light striking the outer surface of the greenhouse actually reaches the plant. This can vary depending on the time of year and whether a coating has been applied to the exterior of the greenhouse in summertime. After entering the greenhouse, only a fraction of the light that reaches the top of the canopy makes it through to reach the lower canopy levels of vine crops (Figure 9).

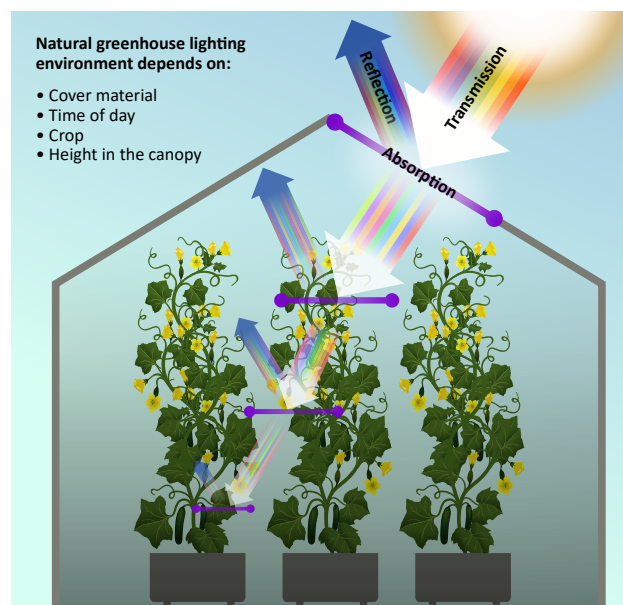
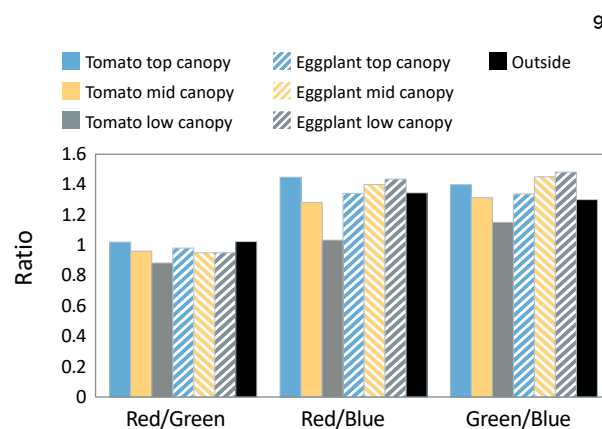
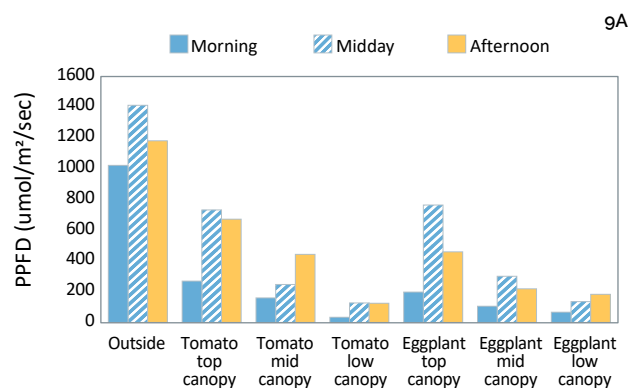


Figure 9. (A) Light quantity and (B) quality outside and at different heights in the canopy of tomatoes and eggplants in a double poly greenhouse in southwestern Ontario in August, 2022. (C) Illustration of the light quantity and quality as light enters the greenhouse and at different heights in the canopy of vine crops.

Light distribution at different heights in the canopy of vine crops can be improved by using glass or plastic coverings with increased diffusion properties. The diffused cover material without anti-reflective coating will reduce the amount of light entering the greenhouse, but the diffused light will reach the lower leaves increasing their photosynthetic capabilities (Figure 10). This results in a more uniform microclimate at the different heights of the canopy, a slightly cooler greenhouse because of increased transpiration (movement of water vapour from the leaf into the atmosphere that occurs through open stomata) and improved production. Glass manufacturers have developed glass with various levels of diffusion. Plastic coverings by their nature have higher diffusive light transmission properties. Coating materials can be applied to the exterior of greenhouses to increase light diffusion. Alternatively, a diffuse shade curtain can be used, which when closed provides some shade to the crop and improves the amount of diffuse light.

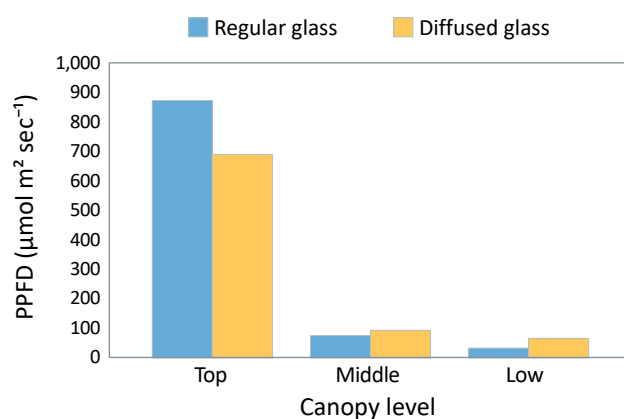


Figure 10. Diffused glass allows more light to reach lower levels of the canopy of a pepper crop compared to regular glass.

Light Intensity and Leaf Size

Leaf size is related to light intensity. This is particularly true for young, expanding leaves: during periods of low light intensity they tend to grow larger, allowing more light to be intercepted and thus improving the overall energy conversion efficiency of the plant. These large leaves are usually thin, with a thinner cuticle layer and are more easily damaged when handled during normal cultural practices. In contrast, leaves grown under high light intensity usually have a thicker cuticle.

In leaves formed under low light conditions, the chloroplasts are aligned perpendicular to the sun radiation. In this configuration they can capture more light energy. However, the degree of response depends on the age of the plant, the age of the leaves and the length of time spent acclimatizing and adjusting to the environmental conditions. This explains, in part, why spring-grown plants are bigger than fall-grown plants, even though the light levels may be the same.



Relative Humidity (RH)

Relative humidity (RH) is the ratio of the actual amount of water vapour present in a given amount of air (the absolute humidity) to the maximum amount of water vapour that can be held within that volume of air at a given temperature. RH is expressed as a percentage and varies between 40% and 100% in most greenhouses. The higher the RH, the more water is present in the air (Table 2). Wet bulb and dry bulb readings, together with psychrometric charts, provide information about the amount of water present in the air, the RH and the dew point. Most computer systems for controlling greenhouse environments automatically provide this information.

The amount of water vapour that air can hold increases with temperature, almost doubling for every 10°C increase in temperature (Table 3). This means that the amount of water in the air required to achieve 70% RH varies with temperature (Table 4). For example, at 20°C and 70% RH, the air can hold only 12.2 g/m³ water. But at 30°C and 70% RH, it can hold 21.9 g/m³ water. This difference affects transpiration and the drying capacity of air.

Table 2. Water Content of Air at Different Levels of Humidity (at 18°C)

Relative Humidity (%)	Water Content (g/m ³)
100	15.7
80	12.6
60	9.4
30	4.7

This table is derived from psychrometric charts.
Source: 2001 ASHRAE Handbook — Fundamentals (American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., 2001).

Table 3. Effect of Temperature on the Water-Holding Capacity of Air

Temperature (°C)	Water Content (g/m ³)
0	4.9
10	9.5
20	17.8
30	31.8

This table is derived from psychrometric charts.
Source: 2001 ASHRAE Handbook — Fundamentals (American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., 2001).

Table 4. Effect of Temperature on Relative Humidity, the Water-Holding Capacity of Air and Vapour Deficit

Temperature (°C)	RH (%)	Max. Potential Water Content (g/m ³)	Actual Water Content (g/m ³)	Vapour Deficit (g/m ³)
20	70	17.6	12.2	5.4
25	70	23.6	16.4	7.2
30	70	31.7	21.9	9.8

This table is derived from psychometric charts.

Source: 2001 ASHRAE Handbook — Fundamentals (American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., 2001).

If the greenhouse air is heated without changing the actual amount of moisture present, the RH will decrease. Conversely, cooling the greenhouse will increase the RH. Where different day and night temperature regimes are established, RH will change accordingly. For instance, many producers increase the temperature at sunrise by about 3°C, thus lowering the RH by 12–18% and increasing the transpiration rate. In the evening, the drop in temperature increases the RH, requiring some ventilation to remove moisture and prevent disease development.

A rule of thumb for most greenhouse conditions is that for each degree Celsius increase in temperature, the RH drops about 4–6%.

When moist air reaches the saturation point, condensation occurs on the cooler surfaces in the greenhouse. During the day, leaves are usually warmer than the surrounding air. At night, the leaf temperature may drop 1°C or 2°C below ambient air temperature due to radiant heat loss. If the greenhouse RH is near 95%, condensation may take place on leaf surfaces. Prolonged periods of high RH and condensation encourage bacterial diseases and the germination of many fungal spores, such as Botrytis or powdery mildew. For more information see Publication 836A: *Integrated Pest Management for Greenhouse Fruits and Vegetables*.

An extremely low RH may occur when large amounts of dry air enter the greenhouse on a bright, sunny day during the early part of the

year. The cooling cycle must be monitored closely during this period. Too much ventilation reduces RH too rapidly and may cause burning of tender foliage or curling of young cucumber fruit, decreasing fruit quality and yield.

Misting or fogging systems that maintain RH can be installed to prevent damage to specific crops. During the summer, when forced ventilation is needed, a high daytime RH is often not a problem, unless a fan and pad system has been installed for cooling. However, ventilation and/or heating are often required at night to prevent excessively high RH and condensation on the foliage.

Note that RH affects pollen transfer. For tomato pollination to occur, RH must be between 70–75%. This permits the proper release of pollen. After pollination, a higher RH helps the pollen to germinate, improving fertilization and increasing fruit size.

Vapour Pressure Deficit (VPD)

Plant vigour and growth rate can be altered by adjusting the **vapour pressure deficit (VPD)**. VPD is the difference between the vapour pressure inside and the air outside of the leaf. The greater the VPD, the greater the rate of transpiration and water loss.

A VPD that is too low results in:

- low transpiration
- thicker and larger leaves
- thick stems

- weaker root systems
- plants that are more prone to disease infestations

A VPD that is too high results in:

- high transpiration
- thinner and smaller leaves
- thinner stems
- stronger root system

Extreme VPD values or rapid increases or decreases in VPD are detrimental to plant growth, fruit quality and plant productivity.

VPD is expressed in kiloPascals (kPa). It is calculated by subtracting the vapour pressure of the air (VP_{air}) from the vapour pressure of the leaf (VP_{leaf}). **Vapour pressure (VP)** is the result of water vapour exerting pressure in the air or within the leaf. It is directly related to temperature and RH. As temperature and RH increase so does VP.

The optimal VPD is 0.5–1.2 kPa. At these VPD values, optimal transpiration rate and nutrient uptake, coupled with adequate sugars, result in healthy, vigorous, high-yielding plants. The VPD can be adjusted in the greenhouse by altering greenhouse air temperatures, RH, venting rates and air movement. Changing how much water is available to the crop also alters the VPD. In general, as the air temperature increases, so should the RH set point to maintain the optimal VPD.

A simple method to calculate VPD is as follows:

1. Determine the VP_{leaf}

- Measure the leaf temperature using an infrared camera or other sensor.
- Since the interior of a healthy leaf is always moist, its RH is assumed to be 100%.
- Look up the VP_{leaf} at 100% RH using an online VP calculator.

2. Determine the VP_{air}

- Measure the air temperature and humidity.
- Look up the VP_{air} using an online VP calculator.

3. Subtract the VP_{air} from the VP_{leaf}

$$VPD = VP_{leaf} - VP_{air}$$

For example, if the leaf temperature is 23°C, the leaf RH is assumed to always be 100%, then **$VP_{leaf} = 2.81$ kPa**.

If the air temperature is 20°C and air RH is 80%, then **$VP_{air} = 1.871$ kPa** (according to an online VP calculator).

$$VPD = 2.81 \text{ kPa} - 1.871 \text{ kPa} = 0.939 \text{ kPa}$$

VPD would be 0.939 kPa. This is within the optimal VPD of 0.5–1.2 kPa.

As greenhouse air temperature increases, so should the RH set point in order to maintain optimum VPD. However, ideal RH levels depend not only on air temperature but leaf temperature as well. As leaf temperature increases above air temperature, so does the RH levels required to maintain optimum VPD. For example, [Table 5](#) shows VPD values if leaf and air temperatures are equal. But [Table 6](#) shows VPD values if leaf temperature is 1°C warmer than air temperature and [Table 7](#) shows VPD values if leaf temperature is 2°C warmer than air temperature. For example, when air and leaf temperature are both 18°C, RH should be maintained between 48–76% in order to achieve a VPD within the optimal range (0.5–1.2 kPa) ([Table 5](#)). However, if the air temperature is 18°C but the leaf temperature is 1 or 2°C warmer, then the RH should be maintained at 52–80% ([Table 6](#)) or 56–88% ([Table 7](#)), respectively.

Conversely, if leaf temperature is cooler than air temperature, then lower RH levels are required to maintain optimum VPD. [Table 8](#) and [Table 9](#) show VPD values if leaf temperature is 1 and 2°C cooler than air temperature, respectively.

Table 5. VPD Values at Different Air Temperatures and RH Levels when Leaf Temperature is Equal to Air Temperature

Legend: Shaded values are within the ideal VPD range of 0.5–1.2 kPa

Temp	Relative Humidity (Leaf T = Air T)																			
	100	96	92	88	84	80	76	72	68	64	60	56	52	48	44	40	36	32	28	24
12	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	1.0	1.0	1.1
13	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.8	0.9	1.0	1.0	1.1	1.2
14	0.0	0.1	0.1	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.9	1.0	1.0	1.1	1.2	1.3
15	0.0	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.0	1.1	1.2	1.2	1.3
16	0.0	0.1	0.1	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.1	1.2	1.2	1.3	1.4
17	0.0	0.1	0.2	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.9	0.9	1.0	1.1	1.2	1.2	1.3	1.4	1.5
18	0.0	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.1	1.2	1.2	1.3	1.4	1.5	1.6
19	0.0	0.1	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.4	1.5	1.6	1.7
20	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
21	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
22	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
23	0.0	0.1	0.2	0.3	0.4	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
24	0.0	0.1	0.2	0.4	0.5	0.6	0.7	0.8	1.0	1.1	1.2	1.3	1.4	1.6	1.7	1.8	1.9	2.0	2.1	2.2
25	0.0	0.1	0.3	0.4	0.5	0.6	0.8	0.9	1.0	1.1	1.3	1.4	1.5	1.6	1.8	1.9	2.0	2.2	2.3	2.4
26	0.0	0.1	0.3	0.4	0.5	0.7	0.8	0.9	1.1	1.2	1.3	1.5	1.6	1.7	1.9	2.0	2.2	2.3	2.4	2.6
27	0.0	0.1	0.3	0.4	0.6	0.7	0.9	1.0	1.1	1.3	1.4	1.6	1.7	1.9	2.0	2.1	2.3	2.4	2.6	2.7
28	0.0	0.2	0.3	0.5	0.6	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.8	2.0	2.1	2.3	2.4	2.6	2.7	2.9
29	0.0	0.2	0.3	0.5	0.6	0.8	1.0	1.1	1.3	1.4	1.6	1.8	1.9	2.1	2.2	2.4	2.6	2.7	2.9	3.0
30	0.0	0.2	0.3	0.5	0.7	0.8	1.0	1.2	1.4	1.5	1.7	1.9	2.0	2.2	2.4	2.5	2.7	2.9	3.1	3.2
31	0.0	0.2	0.4	0.5	0.7	0.9	1.1	1.3	1.4	1.6	1.8	2.0	2.2	2.3	2.5	2.7	2.9	3.1	3.2	3.4
32	0.0	0.2	0.4	0.6	0.8	1.0	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.0	3.2	3.4	3.6
33	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8
34	0.0	0.2	0.4	0.6	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0
35	0.0	0.2	0.4	0.7	0.9	1.1	1.3	1.6	1.8	2.0	2.2	2.5	2.7	2.9	3.1	3.4	3.6	3.8	4.0	4.3

Source: Adapted from Agriculture and Agri-Food Canada.

Table 6. VPD Values at Different Air Temperatures and RH Levels when Leaf Temperature is 1°C Warmer than Air Temperature

Legend: Shaded values are within the ideal VPD range of 0.5–1.2 kPa

Temp	Relative Humidity (Leaf Delta T +1°C)																			
	100	96	92	88	84	80	76	72	68	64	60	56	52	48	44	40	36	32	28	24
12	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.2
13	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.1	1.1	1.2	1.2
14	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.1	1.1	1.2	1.3	1.3
15	0.1	0.2	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.1	1.1	1.2	1.3	1.3	1.4
16	0.1	0.2	0.3	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.4	1.4	1.5
17	0.1	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.4	1.4	1.5	1.6
18	0.1	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.9	1.0	1.0	1.1	1.2	1.3	1.4	1.5	1.5	1.6	1.7
19	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.5	1.6	1.7	1.8
20	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.6	1.7	1.8	1.9
21	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.5	1.6	1.7	1.8	1.9	2.0
22	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.8	1.9	2.0	2.1	2.2
23	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.9	2.0	2.1	2.2	2.3
24	0.2	0.3	0.4	0.5	0.7	0.8	0.9	1.0	1.1	1.3	1.4	1.5	1.6	1.7	1.9	2.0	2.1	2.2	2.3	2.5
25	0.2	0.3	0.4	0.6	0.7	0.8	1.0	1.1	1.2	1.3	1.5	1.6	1.7	1.8	2.0	2.1	2.2	2.3	2.5	2.6
26	0.2	0.3	0.5	0.6	0.7	0.9	1.0	1.1	1.3	1.4	1.5	1.7	1.8	2.0	2.1	2.2	2.4	2.5	2.6	2.8
27	0.2	0.4	0.5	0.6	0.8	0.9	1.1	1.2	1.4	1.5	1.6	1.8	1.9	2.1	2.2	2.4	2.5	2.6	2.8	2.9
28	0.2	0.4	0.5	0.7	0.8	1.0	1.1	1.3	1.4	1.6	1.7	1.9	2.0	2.2	2.3	2.5	2.6	2.8	2.9	3.1
29	0.2	0.4	0.6	0.7	0.9	1.0	1.2	1.4	1.5	1.7	1.8	2.0	2.2	2.3	2.5	2.6	2.8	3.0	3.1	3.3
30	0.2	0.4	0.6	0.8	0.9	1.1	1.3	1.4	1.6	1.8	1.9	2.1	2.3	2.5	2.6	2.8	3.0	3.1	3.3	3.5
31	0.3	0.4	0.6	0.8	1.0	1.2	1.3	1.5	1.7	1.9	2.1	2.2	2.4	2.6	2.8	3.0	3.1	3.3	3.5	3.7
32	0.3	0.5	0.7	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.7	2.9	3.1	3.3	3.5	3.7	3.9
33	0.3	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.1
34	0.3	0.5	0.7	0.9	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.9	3.1	3.3	3.5	3.7	3.9	4.1	4.3
35	0.3	0.5	0.8	1.0	1.2	1.4	1.7	1.9	2.1	2.3	2.6	2.8	3.0	3.2	3.5	3.7	3.9	4.1	4.4	4.6

Source: Adapted from Agriculture and Agri-Food Canada.

Table 7. VPD Values at Different Air Temperatures and RH Levels when Leaf Temperature is 2°C Warmer than Air Temperature**Legend:** Shaded values are within the ideal VPD range of 0.5–1.2 kPa

Temp	Relative Humidity (Leaf Delta T +2°C)																											
	100	96	92	88	84	80	76	72	68	64	60	56	52	48	44	40	36	32	28	24	20	16	12	8	4	0		
12	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.3	1.3	1.4	1.4	1.5	1.5	1.6		
13	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.0	1.1	1.2	1.2	1.3	1.3	1.4	1.5	1.5	1.6	1.6	1.7		
14	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.1	1.1	1.2	1.2	1.3	1.4	1.4	1.5	1.6	1.6	1.7	1.8	1.8		
15	0.2	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.7	1.8	1.9	1.9		
16	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.0	1.1	1.2	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.8	1.8	1.9	2.0	2.1		
17	0.3	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.9	1.0	1.0	1.1	1.2	1.3	1.3	1.4	1.5	1.6	1.7	1.7	1.8	1.9	2.0	2.0	2.1	2.2		
18	0.3	0.4	0.4	0.5	0.6	0.7	0.8	0.9	0.9	1.0	1.1	1.2	1.3	1.3	1.4	1.5	1.6	1.7	1.8	1.8	1.9	2.0	2.1	2.2	2.3	2.3		
19	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.2	2.3	2.4	2.5		
20	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.6		
21	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8		
22	0.3	0.4	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.5	2.6	2.7	2.8	2.9	3.0		
23	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.1	3.2		
24	0.4	0.5	0.6	0.7	0.9	1.0	1.1	1.2	1.3	1.5	1.6	1.7	1.8	1.9	2.0	2.2	2.3	2.4	2.5	2.6	2.8	2.9	3.0	3.1	3.2	3.4		
25	0.4	0.5	0.7	0.8	0.9	1.0	1.2	1.3	1.4	1.5	1.7	1.8	1.9	2.0	2.2	2.3	2.4	2.6	2.7	2.8	2.9	3.1	3.2	3.3	3.4	3.6		
26	0.4	0.6	0.7	0.8	1.0	1.1	1.2	1.4	1.5	1.6	1.8	1.9	2.0	2.2	2.3	2.4	2.6	2.7	2.8	3.0	3.1	3.2	3.4	3.5	3.6	3.8		
27	0.4	0.6	0.7	0.9	1.0	1.2	1.3	1.4	1.6	1.7	1.9	2.0	2.2	2.3	2.4	2.6	2.7	2.9	3.0	3.1	3.3	3.4	3.6	3.7	3.9	4.0		
28	0.5	0.6	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.8	2.0	2.1	2.3	2.4	2.6	2.7	2.9	3.0	3.2	3.3	3.5	3.6	3.8	3.9	4.1	4.2		
29	0.5	0.6	0.8	1.0	1.1	1.3	1.4	1.6	1.8	1.9	2.1	2.2	2.4	2.6	2.7	2.9	3.1	3.2	3.4	3.5	3.7	3.9	4.0	4.2	4.3	4.5		
30	0.5	0.7	0.9	1.0	1.2	1.4	1.5	1.7	1.9	2.0	2.2	2.4	2.5	2.7	2.9	3.1	3.2	3.4	3.6	3.7	3.9	4.1	4.2	4.4	4.6	4.8		
31	0.5	0.7	0.9	1.1	1.3	1.4	1.6	1.8	2.0	2.2	2.3	2.5	2.7	2.9	3.1	3.2	3.4	3.6	3.8	4.0	4.1	4.3	4.5	4.7	4.9	5.0		
32	0.6	0.8	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.8	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.7	4.9	5.1	5.3		
33	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.4	5.6		
34	0.6	0.8	1.0	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.5	4.7	4.9	5.1	5.3	5.5	5.7	5.9		
35	0.7	0.9	1.1	1.3	1.6	1.8	2.0	2.2	2.5	2.7	2.9	3.1	3.4	3.6	3.8	4.0	4.3	4.5	4.7	4.9	5.2	5.4	5.6	5.8	6.0	6.3		

Source: Adapted from Agriculture and Agri-Food Canada.

Table 8. VPD Values at Different Air Temperatures and RH Levels when Leaf Temperature is 1°C Cooler than Air Temperature**Legend:** Shaded values are within the ideal VPD range of 0.5–1.2 kPa

Temp	Relative Humidity (Leaf Delta T -1°C)																											
	100	96	92	88	84	80	76	72	68	64	60	56	52	48	44	40	36	32	28	24	20	16	12	8	4	0		
12	-0.1	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.3	1.3		
13	-0.1	0.0	0.0	0.1	0.1	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.0	1.1	1.2	1.2	1.3	1.3	1.4		
14	-0.1	0.0	0.0	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.1	1.1	1.2	1.2	1.3	1.4	1.4	1.5		
15	-0.1	0.0	0.0	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.3	1.4	1.5	1.5	1.6		
16	-0.1	0.0	0.0	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.3	1.4	1.5	1.6	1.6	1.7		
17	-0.1	0.0	0.0	0.1	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.0	1.1	1.2	1.3	1.4	1.4	1.5	1.6	1.7	1.7	1.8		
18	-0.1	0.0	0.0	0.1	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.9	0.9	1.0	1.1	1.2	1.3	1.4	1.4	1.5	1.6	1.7	1.8	1.9	1.9		
19	-0.1	0.0	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1		
20	-0.1	0.0	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2		
21	-0.1	0.0	0.1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3		
22	-0.2	-0.1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.9	2.0	2.1	2.2	2.3	2.4	2.5		
23	-0.2	-0.1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6		
24	-0.2	-0.1	0.1	0.2	0.3	0.4	0.5	0.7	0.8	0.9	1.0	1.1	1.3	1.4	1.5	1.6	1.7	1.9	2.0	2.1	2.2	2.3	2.5	2.6	2.7	2.8		
25	-0.2	-0.1	0.1	0.2	0.3	0.4	0.6	0.7	0.8	1.0	1.1	1.2	1.3	1.5	1.6	1.7	1.8	2.0	2.1	2.2	2.4	2.5	2.6	2.7	2.9	3.0		
26	-0.2	-0.1	0.1	0.2	0.3	0.5	0.6	0.7	0.9	1.0	1.2	1.3	1.4	1.6	1.7	1.8	2.0	2.1	2.2	2.4	2.5	2.6	2.8	2.9	3.0	3.2		
27	-0.2	-0.1	0.1	0.2	0.4	0.5	0.7	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.8	1.9	2.1	2.2	2.4	2.5	2.6	2.8	2.9	3.1	3.2	3.4		
28	-0.2	-0.1	0.1	0.2	0.4	0.5	0.7	0.8	1.0	1.1	1.3	1.4	1.6	1.8	1.9	2.1	2.2	2.4	2.5	2.7	2.8	3.0	3.1	3.3	3.4	3.6		
29	-0.2	-0.1	0.1	0.3	0.4	0.6	0.7	0.9	1.1	1.2	1.4	1.5	1.7	1.9	2.0	2.2	2.3	2.5	2.7	2.8	3.0	3.1	3.3	3.5	3.6	3.8		
30	-0.2	-0.1	0.1	0.3	0.4	0.6	0.8	1.0	1.1	1.3	1.5	1.6	1.8	2.0	2.1	2.3	2.5	2.6	2.8	3.0	3.2	3.3	3.5	3.7	3.8	4.0		
31	-0.2	-0.1	0.1	0.3	0.5	0.6	0.8	1.0	1.2	1.4	1.5	1.7	1.9	2.1	2.3	2.4	2.6	2.8	3.0	3.2	3.3	3.5	3.7	3.9	4.1	4.2		
32	-0.3	-0.1	0.1	0.3	0.5	0.7	0.9	1.1	1.3	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.5	3.7	3.9	4.1	4.3	4.5		
33	-0.3	-0.1	0.1	0.3	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.2	4.4	4.6	4.8		
34	-0.3	-0.1	0.1	0.3	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5	3.8	4.0	4.2	4.4	4.6	4.8	5.0		
35	-0.3	-0.1	0.1	0.4	0.6	0.8	1.0	1.3	1.5	1.7	1.9	2.2	2.4	2.6	2.8	3.1	3.3	3.5	3.7	4.0	4.2	4.4	4.6	4.9	5.1	5.3		

Source: Adapted from Agriculture and Agri-Food Canada.

Table 9. VPD Values at Different Air Temperatures and RH Levels when Leaf Temperature is 2°C Cooler than Air Temperature

Legend: Shaded values are within the ideal VPD range of 0.5–1.2 kPa

Temp	Relative Humidity (Leaf Delta T -2°C)																				
	100	96	92	88	84	80	76	72	68	64	60	56	52	48	44	40	36	32	28	24	20
12	-0.2	-0.1	-0.1	0.0	0.0	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	0.9
13	-0.2	-0.1	-0.1	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.8	0.9	1.0	1.0
14	-0.2	-0.1	-0.1	0.0	0.1	0.1	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.9	1.0	1.0	1.1
15	-0.2	-0.1	-0.1	0.0	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.0	1.1	1.2
16	-0.2	-0.1	-0.1	0.0	0.1	0.1	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.1	1.2	1.3
17	-0.2	-0.2	-0.1	0.0	0.1	0.2	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.9	0.9	1.0	1.1	1.2	1.2	1.3
18	-0.2	-0.2	-0.1	0.0	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.1	1.2	1.2	1.3	1.4
19	-0.3	-0.2	-0.1	0.0	0.1	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.4	1.5
20	-0.3	-0.2	-0.1	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6
21	-0.3	-0.2	-0.1	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7
22	-0.3	-0.2	-0.1	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
23	-0.3	-0.2	-0.1	0.0	0.1	0.2	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.3	1.4	1.5	1.6	1.7	1.8	1.9
24	-0.3	-0.2	-0.1	0.0	0.1	0.3	0.4	0.5	0.6	0.7	0.9	1.0	1.1	1.2	1.3	1.5	1.6	1.7	1.8	1.9	2.0
25	-0.4	-0.2	-0.1	0.0	0.1	0.3	0.4	0.5	0.7	0.8	0.9	1.0	1.2	1.3	1.4	1.5	1.7	1.8	1.9	2.0	2.2
26	-0.4	-0.2	-0.1	0.0	0.2	0.3	0.4	0.6	0.7	0.8	1.0	1.1	1.2	1.4	1.5	1.6	1.8	1.9	2.0	2.2	2.3
27	-0.4	-0.3	-0.1	0.0	0.2	0.3	0.5	0.6	0.7	0.9	1.0	1.2	1.3	1.5	1.6	1.7	1.9	2.0	2.2	2.3	2.5
28	-0.4	-0.3	-0.1	0.0	0.2	0.3	0.5	0.6	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.8	2.0	2.2	2.3	2.5	2.6
29	-0.4	-0.3	-0.1	0.0	0.2	0.4	0.5	0.7	0.8	1.0	1.2	1.3	1.5	1.6	1.8	2.0	2.1	2.3	2.4	2.6	2.8
30	-0.5	-0.3	-0.1	0.0	0.2	0.4	0.6	0.7	0.9	1.1	1.2	1.4	1.6	1.7	1.9	2.1	2.3	2.4	2.6	2.8	2.9
31	-0.5	-0.3	-0.1	0.1	0.2	0.4	0.6	0.8	1.0	1.1	1.3	1.5	1.7	1.8	2.0	2.2	2.4	2.6	2.7	2.9	3.1
32	-0.5	-0.3	-0.1	0.1	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.3	2.5	2.7	2.9	3.1	3.3
33	-0.5	-0.3	-0.1	0.1	0.3	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5
34	-0.6	-0.4	-0.1	0.1	0.3	0.5	0.7	0.9	1.1	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.1	3.3	3.5	3.7
35	-0.6	-0.4	-0.1	0.1	0.3	0.5	0.8	1.0	1.2	1.4	1.7	1.9	2.1	2.3	2.6	2.8	3.0	3.2	3.5	3.7	3.9

Source: Adapted from Agriculture and Agri-Food Canada.



CHAPTER 5

Carbon Dioxide (CO₂)

When exposed to light, plants grow by converting carbon dioxide (CO₂) and water into sugar and oxygen; this is a simple way to view **photosynthesis**. About half of the amount of CO₂ that is fixed by plants during photosynthesis is released back into the atmosphere during **respiration**. This input and output of CO₂ is a process that happens by diffusion through the leaf stomata. Open stomata will facilitate this exchange and closed stomata will hinder it.

Ambient CO₂ levels in 2023 were around 400 parts per million (ppm). These levels fluctuate with the seasons. CO₂ levels increase with warmer spring weather that promotes aerobic activity to breakdown dead organic material, and they peak in early summer when vegetation is in full bloom undergoing photosynthesis and consuming CO₂. The consumption of CO₂ continues as the growing season progresses until the atmospheric levels reach a low at the end of the season. The cycle begins again with the

breakdown of dead organic matter in autumn and winter which releases CO₂ back into the atmosphere.

What is CO₂?

CO₂ is composed of one carbon (C) and two oxygen (O) atoms. It is a colourless and odourless gas at room temperature, but under higher pressure CO₂ gas is converted into liquid. Solid CO₂, better known as dry ice, is produced under high pressure and low temperatures. CO₂ gas is soluble in water where it forms a weak acid known as carbonic acid (H₂CO₃). It is more dense than dry air, and it is transparent to visible light. However, CO₂ gas absorbs and reemits infrared radiation. This allows it to trap heat and act as a greenhouse gas in the earth's atmosphere.

CO₂ Enrichment and Plant Physiology

Crops grown in controlled environment agriculture (CEA) production systems, such as greenhouses and vertical farms, consume

CO₂ as they undergo photosynthesis when exposed to light. A typical greenhouse crop will use 4.8–9.6 kg/hr/acre. This process can drop the concentration of CO₂ from ambient levels (around 400 ppm) to as low as 100 ppm if the production site is not ventilated. Such low levels of CO₂ can cause significant plant health issues and losses in productivity. It is recommended to ventilate a fruit or vegetable greenhouse at a rate of 1 air exchange per hour to replenish the CO₂ in the growing space.

Enriching the air of greenhouses with CO₂, sometimes referred to as CO₂ fertilization, has also become common practice. It is typically done by using flue gas from boilers that burn natural gas to generate heat and CO₂, or by purchasing liquid CO₂ that is vaporized and pumped into the greenhouse (Figure 11).



Figure 11. Natural gas boiler (bottom portion) with flue gas scrubber (top portion) to provide heat and CO₂ for greenhouse vegetable production.

The quality of CO₂ derived from flue gas must be monitored to ensure there are no harmful side effects from byproducts such as ethylene (C₂H₄), nitric oxide (NO), nitrogen

dioxide (NO₂) and/or carbon monoxide (CO). More information on ways to enrich greenhouses with CO₂ can be found in the ministry's factsheet entitled [Supplemental Carbon Dioxide in Greenhouses](#) available on [ontario.ca](#).

CO₂ levels affect photosynthesis, transpiration, fruit quality and stress tolerance in the following ways:

1. Photosynthesis

Plants uptake CO₂ through their stomata by diffusion. Therefore, the higher the level of CO₂ outside the leaf, the higher the level inside the leaf. Higher levels of CO₂ lead to more photosynthesis and are associated with a 15–30% increase in fruit and vegetable production, on average. Increases in production have been observed as high as 50% in tomatoes and peppers and 73% in cucumbers. One study showed an increase of 72% in lettuce head mass when plants were grown under 1,000 ppm as compared to 200 ppm CO₂. However, a growing environment with more than 1,200 ppm of CO₂ resulted in lower rates of photosynthesis and reduced yield for greenhouse cucumbers.

Alongside the level of CO₂ in the growing environment, the duration of the exposure of plants to CO₂ enrichment also affects photosynthesis (**dose = quantity and duration**). If plants are exposed to elevated levels of CO₂ for an extended period, they undergo a process called **photosynthetic acclimation** where the rate of photosynthesis drops, and the benefits of elevated levels of CO₂ are not as pronounced as they were when the plants were first exposed to them. This drop in photosynthetic activity may be associated with a drop in chlorophyll content and a build-up of starch and other sugars in the leaves that may interfere with the function of chloroplasts. Decreased chloroplast function can in turn lead to reduced photosynthesis and plant

productivity. As a result of prolonged CO₂ enrichment, plant leaves may become chlorotic, deformed, rolled and brittle. This is thought to be due to an imbalance in the ratio of carbon and nitrogen in the plant. One way to reduce photosynthetic acclimation in the crop is by feeding it high levels of nitrogen (N). For example, cucumbers that were grown with high N exhibited less photosynthetic acclimation than those that were grown with lower N levels.

2. Transpiration

When greenhouse CO₂ concentration is elevated above ambient levels, it triggers partial closure of stomates resulting in lower stomatal conductance (less gas exchange) and transpiration rates in plants: almost 10% less in some cases. Therefore, less water is evaporating from the leaves through the stomata, and less water is being taken up by the plant. This reduction in transpiration can increase the water use efficiency by up to 60% in plants and allows producers to reduce their water bill. However, lower rates of transpiration can be detrimental to plants on a hot day because transpiration is one of the primary ways plants cool themselves when greenhouses reach high temperatures. The reduction in stomatal conductance and transpiration by CO₂ enrichment is more severe under cloudy (low light) than sunny (high light) conditions. This effect also varies with plant species and is more pronounced in eggplants compared to tomatoes, cucumbers and peppers. Therefore, CO₂ enrichment should be minimized during hot days, especially on cloudy days and on eggplants to allow plants to maximize their transpiration rate and their ability to cool down.

3. Food Quality

In general, elevated levels of CO₂ increase sugar and antioxidant levels and decrease protein and mineral levels in fruits and vegetables. However, variability does exist between different crops and different cultivars of the same crop depending on the

concentration of CO₂. Some tomato plants, for example, may produce higher quality and better tasting fruit under elevated CO₂ conditions, whereas other tomato plants may have reduced levels of lycopene - the pigment that gives tomatoes their red colour. Also, some cucumbers grown under high CO₂ levels have elevated levels of sugar, but lower levels of dietary fibre. The colour of lettuce and strawberry crops can change depending on the level of CO₂ they are grown in, and higher levels of healthy compounds have been observed in lettuce grown under CO₂ enriched conditions. Overall, plants produce larger fruit that have lower mineral nutrient concentrations when grown under elevated CO₂ levels. This may be due to a dilution effect when plants increase their fruit size, but they don't produce more mineral nutrients to fill the larger fruit.

The effect of high levels of CO₂ on sugar and protein levels in the fruit is also dependent on the availability of nutrients for the crop. This is similar to the effect of N on photosynthetic acclimation. Studies have shown that under low N and high CO₂ concentrations cucumber quality improved, but no increase in yield was observed. In contrast, when cucumbers were grown under high N and high CO₂ levels their yield increased, but the concentration of sugar and dietary fibre in the fruit did not change. Similarly in tomatoes, the effect of CO₂ enrichment on the levels of sugars and lycopene can be positive or negative depending on the nutrient levels available to the crop.

4. Improved Stress Tolerance

CO₂ enrichment enhances the ability of plants to tolerate stresses like drought and heat because of elevated levels of soluble sugars and antioxidants. These compounds help protect plant cells from damage in stressful growing conditions. Under hot conditions, this can be counteracted by the associated reduction in transpiration rates that may be detrimental, as mentioned above.

CO₂ Enrichment and High Light and Heat

In general, the increase in photosynthesis when crops are grown under high CO₂ levels is greater at higher light levels than at lower light levels. Does that mean that increasing both CO₂ and light levels is a good idea? Not necessarily. For example, it has been shown that CO₂ enrichment increases antioxidant levels in lettuce when grown under high light conditions and when grown under a higher red to blue light ratio. However, high light levels have the opposite effect on sugar levels because high light does not increase sugar levels in lettuces as lower light levels do under CO₂ enriched conditions.

Another study showed that CO₂ enrichment reduced yield of marketable tomato fruit during bright and hot days of August in southwestern Ontario. Furthermore, tomato plants grown under high CO₂ and high light conditions may suffer from short leaf syndrome (SLS) where plants develop short, thick, curled and crisp, dark grey-green leaves. SLS has been shown to be aggravated by not only high light, but also high temperatures (Figure 12). One of the reasons for SLS is high temperatures, especially high nighttime temperatures, that reduce tomato fruit setting. Less severe SLS was observed when plants were grown in high plant density because it may have resulted in more shade and lower light levels in the crop canopy. Therefore, one practical solution to prevent SLS is to use high stem density by introducing additional stems in the spring.



Figure 12. Tomato plants during bright and hot days in August 2005, in Ontario grown under (A) ambient CO₂ levels and (B) CO₂ enrichment. The red circles denote normal leaf development under ambient CO₂ and SLS under CO₂ enrichment.
Source: Agriculture and Agri-Food Canada.

Is CO₂ Enrichment Always a Good Idea?

Based on the data presented in this chapter, it is recommended that greenhouses maintain CO₂ levels around 1,000 ppm on sunny days, 600 to 700 ppm on cloudy days when vents are closed and 400 ppm when vents are open more than 10%. However, greenhouse producers might also want to consider reducing CO₂ levels during hot days, especially on cloudy days. Just like other environment parameters, proper control of greenhouse CO₂ levels relies on properly functioning sensors. CO₂ sensors should be calibrated on a regular basis according to manufacturers' recommendations to ensure accurate measurements. As greenhouse environment control systems become more dynamic with more sophisticated decision-making algorithms that optimize set points in real time, so too will CO₂ control.

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CHAPTER 6

Water

Water supply and water quality are very important for greenhouse crop production. Select a site with an ample supply of high-quality water. To meet the needs of a fully grown crop, the irrigation system must be able to deliver at least 8 litres per metre squared per day ($L/m^2/day$). Some fully grown greenhouse crops (e.g., cucumbers) may require up to 5 $L/plant/day$ during the sunny summer months (Figure 13).

Many greenhouse operations in southwestern Ontario use municipal water. Other operations rely on well water or rain water collected in cisterns or ponds (Figure 14). In most areas, municipal water is of adequate quality, with total soluble salts less than 0.750 milliSiemens per centimetre (mS/cm). When utilizing raw well water, which may be of poor quality, it is important to test the water for microbial, chemical and mineral content before using for routine irrigation. Untreated river or stream waters are not recommended due to the elevated risk of persistent and/or transient

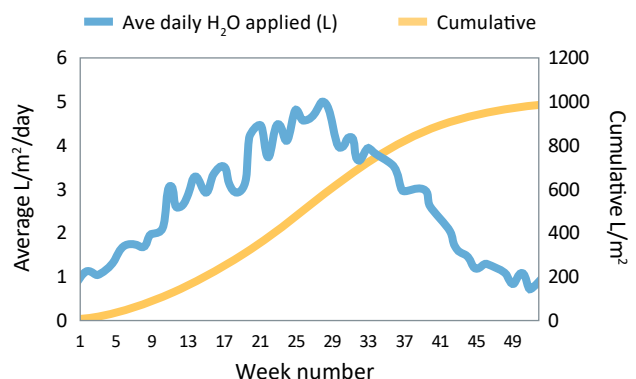


Figure 13. Water application in greenhouse vegetables.

Source: Agriculture and Agri-Food Canada, Harrow Research and Development Centre.



Figure 14. Greenhouse irrigation pond.

upstream contamination that could negatively affect crops. Generally, water quality for greenhouse use may be divided into three classes (Table 10).

Class 1 — water is good for all irrigation purposes. Most water obtained from Lake Erie and Lake Ontario falls within this category.

Class 2 — water should only be used in substrate and soil culture if adequate leaching can take place. It is unsuitable for nutrient film technique (NFT) and for salt-sensitive crops grown in sub-irrigation systems.

Class 3 — water is not recommended for salt-sensitive crops (e.g., cucumber) or crops grown in a limited root volume or in recirculating systems. If the salt level measured by electrical conductivity (EC) exceeds 1.5 mS/cm, it is considered marginally suitable for greenhouse irrigation. In some cases, crops can be grown, but yields may be reduced as a result. The toxic concentration for sodium (Na) is lower than that for chloride (Cl). It may interfere with the uptake of potassium, calcium and magnesium. Some crops (e.g., cucumber) are chloride sensitive. Note that for most areas in Ontario, Na levels are low in well water, while sulphates can be relatively high in the aquifers. Most crops do not require more than 100 ppm of sulphates (33 ppm elemental sulphur) to meet their nutritional requirement for sulphur.

The quality of irrigation water is more important in hydroponic/soilless culture than in soil (Table 11). Always consider water quality when establishing a fertilization program. For example, if the water contains large amounts of calcium or magnesium (e.g., in well water from limestone/dolomite aquifers), reduce the rates of calcium nitrate and magnesium sulphate accordingly. Any nitrogen lost because of these adjustments

can be made up by increasing the amount of another nitrogen-containing fertilizer (e.g., ammonium nitrate). Note that certain elements such as iron, zinc and manganese can be high in some water supplies, particularly untreated well water.

To create **fertigation** schedules (fertilizer and irrigation) for greenhouse vegetable crops, use water with Na levels below 50 ppm and Cl levels below 70 ppm. If the water contains more than 100 ppm Na or 140 ppm Cl, find alternative water sources or use a water purification system, such as reverse osmosis (RO), to dilute or remove those ions. Tomato crops may be grown in a nutrient solution containing 100 ppm Cl without too much difficulty. However, it is best to select a water source that is low in these two elements. Rainwater is low in both Na and Cl; however, if used, be sure to adjust the level of bicarbonate as it will be too low for proper solution management. To raise it, add potassium bicarbonate to the water (not to the stock solutions). If the bicarbonate in the water supply is higher than 60 ppm, add phosphoric and/or nitric acid to achieve the desired pH (5.5–5.8).

Fertigation frequency and amount can be programmed such that watering is activated by variables such as light, growing medium water content or weight or a combination of these factors. Light sensors allow for the calculation of the amount of light that is in the greenhouse and trigger irrigation based on the total amount of light received since the last irrigation event. Water content sensors can trigger watering when the rootzone becomes too dry. These types of precision agriculture techniques have been shown to significantly reduce water use when compared to watering that is based on pre-set time intervals because they allow for flexibility during cloudy days when less watering is required compared to sunny days when more water is required.

Table 10. Classification of Water Quality Based on Salt Content

Class	Electrical Conductivity (mS/cm) ¹	Sodium (ppm)	Chloride (ppm)	Sulphate (ppm)
1	0.5	<30	<50	<100
2	0.5–1	30–60	50–100	100–200
3	1.0–1.5	60–90	100–150	200–300

¹ 1 mS/cm = 1 mmhos/cm or 1,000 µS/cm = 1,000 µmhos/cm

Notes: This table is a guideline to assess the water quality for use in greenhouse vegetable production.

Chloride-sensitive crops (e.g., cucumbers) should be grown only in Class 1 water.

Sodium and chloride are normally found in the ratios presented in this table. If sodium levels are in the 30–60 ppm range, for example, chloride levels will likely fall in the range of 50–100 ppm. If this is not the case, the class of water is based on the level of the more concentrated ion.

Table 11. Recommended Characteristics of Source Water

Characteristic	Level	Characteristic	Level (ppm)	Characteristic	Level (ppm)
Electrical conductivity (EC) (mS/cm)	0–0.5	Nitrogen (N), Nitrate (NO ₃), Ammonium (NH ₄)	<5	Iron (Fe)	<1
pH	5.4–6.8	Phosphorus (P)	<1	Boron (B)	<0.3
Alkalinity, Carbonate (CaCO ₃), Bicarbonate (HCO ₃) (ppm)	40–65	Potassium (K)	<10	Copper (Cu)	<0.1
Hardness (CaCO ₃) (ppm)	<100	Calcium (Ca)	<60	Zinc (Zn)	<0.2
Sodium (Na) (ppm)	<50	Sulfates (SO ₄)	<30	Aluminum (Al)	<2
Chloride (Cl) (ppm)	<71	Magnesium (Mg)	<5	Chloride (Cl)	<2
Sodium Adsorption Ratio	<4	Manganese (Mn)	<1	Fluoride (F)	<1



CHAPTER 7

Nutrient Solution Recycling and Disinfection

Discharge of nutrient solution from the greenhouse operation into surrounding surface and groundwater bodies has negative environmental impacts (e.g., eutrophication, elevated temperatures, chemical contaminants, etc.). Nutrient solution recycling not only reduces water discharge, but also reduces water use in a greenhouse operation by 25–30% and decreases the use of fertilizer by 30–40%. Greenhouse producers typically aim for approximately 25% of the applied fertigation solution to leach out of the rootzone. This ensures adequate watering while avoiding buildup of fertilizer salts in the growing substrate.

Although nutrient solution recycling is an efficient use of resources, there are points of concern that must be considered when capturing and reapplying fertigation runoff water (leachate). As the nutrient solution

passes through the rootzone, the plants take up nutrients and excrete chemicals which change the overall composition of the nutrient solution. To recirculate the leachate, the nutrient levels, electrical conductivity (EC) and pH of the leachate must be readjusted before being fed back to the crop ([Figure 15](#)).

Another concern with recirculating nutrient solution is the potential for pathogen proliferation via the watering system. Over time, microbes will build up in recirculated water, including fungi, oomycetes, bacteria and viruses. This can lead to the development of root diseases caused by, but not limited to, *Phytophthora* and *Pythium* species. But not all microbes that live in recirculated water systems are bad. Many are not pathogenic to the crop and can, in fact, be beneficial by competing with pathogens (microbes that cause disease) for nutrients and living space. Further, there is emerging research to suggest some beneficial microorganisms may also directly improve plant health and productivity (e.g., *Rhizobacteria*). For more information, see Publication 836A: *Integrated Pest Management for Greenhouse Fruits and Vegetables*.

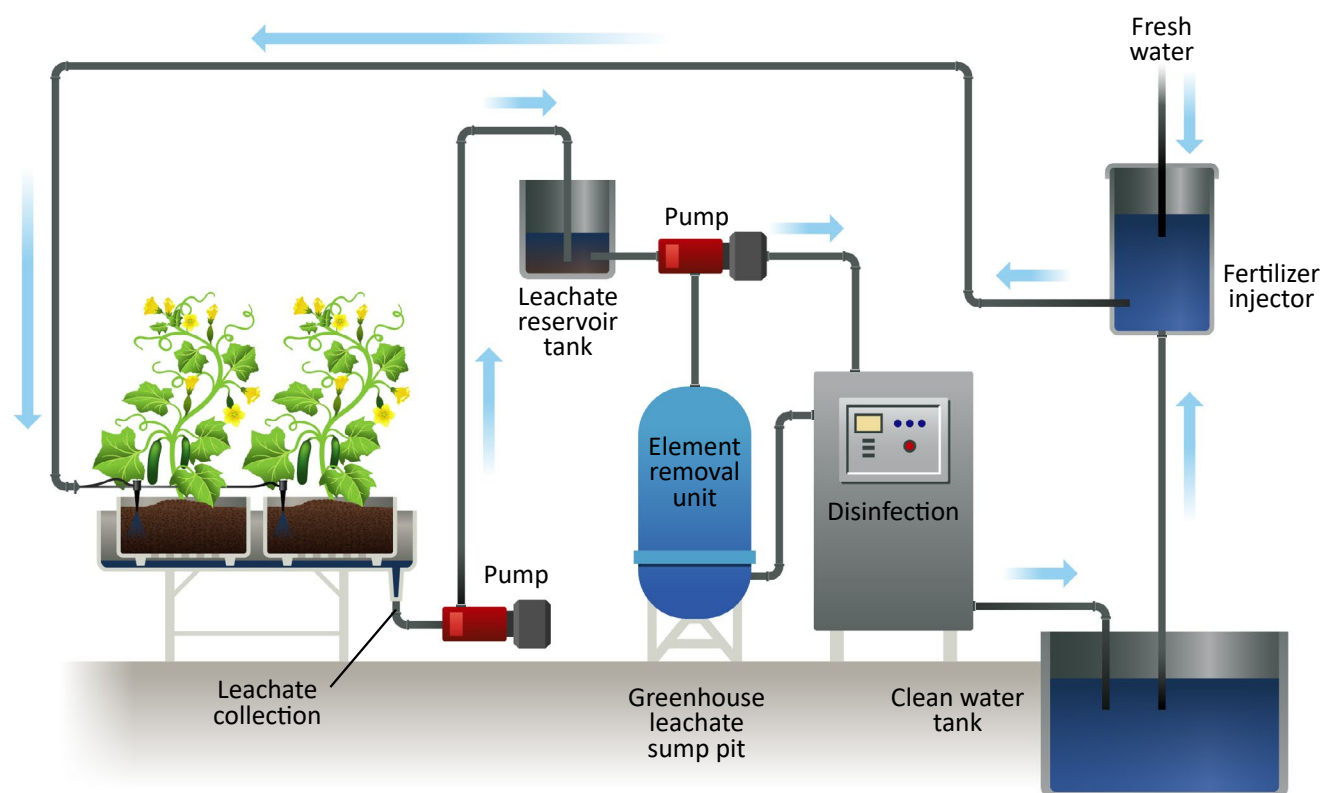


Figure 15. Nutrient solution recycling layout.

To avoid disease development, it is recommended that greenhouses install site-specific filtration and disinfection equipment to reduce the pathogen load of the recycled water. This section provides an overview of water filtration and disinfection technologies that are being used in greenhouses. It outlines the benefits and drawbacks of the most popular systems currently used in greenhouses, including physical filtration (membrane filters), biofiltration, heat treatment (pasteurization), ultraviolet (UV) light and ozone treatment. Special attention is paid to whether a system encourages beneficial microbe growth while reducing pathogen levels. A systems approach should be considered when designing greenhouse recirculated water treatment systems. For information on chemical and biocontrol management options, see Publication 836A: *Integrated Pest Management for Greenhouse Fruits and Vegetables*.

Membrane Filters

The ability of membrane filters to remove pathogens from recirculated water depends on the size of their pores. As the size of the pores decreases, so does the size of microbes that can pass through the filter (Table 12).

The size range of most fungi is 3–50 micrometres (μm), bacteria are between 0.6–3.5 μm and viruses are the smallest at around 0.03–0.3 μm . Filters suitable for removal of microbes have a pore size of $< 10 \mu\text{m}$. **Microfilters** remove particles $\geq 50 \mu\text{m}$, **ultrafilters** remove particles $\geq 0.02 \mu\text{m}$ (20 nanometres (nm)), **nanofilters** remove particles $> 0.01 \mu\text{m}$ (10 nm) and **hyperfilters** (those used in reverse osmosis (RO)) remove particles $\geq 0.0001 \mu\text{m}$ (0.1 nm) (Figure 16). Filters with larger pores (5–7 μm) are effective at removing the oomycetes *Phytophthora* and *Pythium*.

Table 12. Size Range of Microorganisms and Membrane Filter Pores

Microorganism	Size Range (micrometres (µm))
Fungi	3–50
Bacteria	0.6–3.5
Viruses	0.03–0.3
Filter Type	Pore Size Range (micrometres (µm))
Microfilters	50
Ultrafilters	0.02
Nanofilters	0.01
Hyperfilters	0.0001

**Figure 16.** Reverse osmosis filtration system.

Membrane filtration is most effective at controlling pathogens when set up in a series of multi-stage filters (large to small pore size) to avoid rapid clogging of the finer filters. Producers should start with a coarse screen filter to remove debris followed by a series of decreasing pore size filters. One thing to keep in mind is that the size of the filter pores not only restricts microbe passage but also water passage, resulting in backpressure on the system. As the filter pore size gets

smaller the flow rate of water decreases and greater pressure is needed to maintain flow. Depending on the filter pore size, the flow rate can vary between 20–60 L/min. Therefore, filters with small pores that reduce the flow rate may not be ideal for operations that require large volumes of water. Alternatively, the configuration of the filters can be modified (e.g., multiple polishing filters on distribution lines or a group of filters running in parallel) but capital and maintenance costs need to be factored into this added complexity.

Benefits of Membrane Filters

- Membrane screen filters are recommended as a basic first step in a water treatment system to reduce the amount of debris and organic matter in the water such as soil, plant tissue and precipitated nutrients. Debris and organic matter can reduce the efficacy of other treatments such as heat (pasteurization), UV light and ozone as discussed below.
- Using filters in a multi-step manner such that filters with large pore sizes are followed by filters with smaller pore sizes reduces the occurrence of clogging.
- Filters do not require chemicals hence there is no concern of phytotoxicity (crop damage due to chemicals).
- Hyperfilters used in RO can be used to not only remove pathogens, but also remove excess salts such as sodium and chloride. This can be used to improve the quality of some water sources. For example, wells may have high levels of salt.

Drawbacks of Membrane Filters

- Filters do not discriminate between beneficial and pathogenic microbes. All microbes are filtered based on their size.
- Filters have higher installation costs than some other disinfection systems.

- The smaller the pore size, the lower the flow rate of water. If the operation's water requirement is high, it may require a high flow rate of water offered by filters with larger pore sizes, or multiple distributed smaller pore size filters. If larger pore size filters are used, then there is a greater chance for microbes to pass through the filtration system and back to the crop. Alternatively, a side stream or by-pass approach can be used in certain circumstances.
- Filters can be clogged by suspended solids (sand, silt, organic matter), chemical precipitates (iron (Fe), manganese (Mn), carbonates, pesticides), biofilms and algae. This may require a backwashing step that, although effective, adds to system complexity and overall water use.
- Filters will not work properly if they are damaged. They need to be replaced and/or maintained on a regular basis to reduce the risk of leakage or breakthrough. Small-scale leaks are not easily detected and there is no warning system to let producers know that a filter is damaged or that breakthrough is occurring.
- RO removes nutrients so it should only be used for the filtering of external water sources such as wells and municipal sources.

Slow Sand Filtration and Biofiltration

Slow sand filters and biofilters consist of a sand-based (or similar) filter bed that allows the slow passage of water through the media which supports a community of beneficial microbes that consume the organic material entering the filter (Figure 17). The filter material is usually sand, but it can also be granulated stone wool, lava grain, pumice or anthracite. It is recommended to have a minimum filter bed thickness of 50–80 cm and sand grain size of less than 2 mm. The filter is typically supported by layers of gravel underneath. Water typically passes very slowly through the filter material at a rate of 100–300 L/m²/hr. The force of gravity is used to push/pull water through the system. A water layer above the filter of about 80–150 cm is required to generate enough hydrostatic pressure on the column to facilitate adequate flow. After some time, a biologically active layer forms on the top of the filter with a population of algae, bacteria, fungi and other microbes that form biofilms. This layer is called the Schmutzdecke and it is key to reducing pathogens. The filter material physically traps inorganic and organic particles including pathogens. The biological and chemical activity of the Schmutzdecke breaks down the trapped particles and kills pathogens.

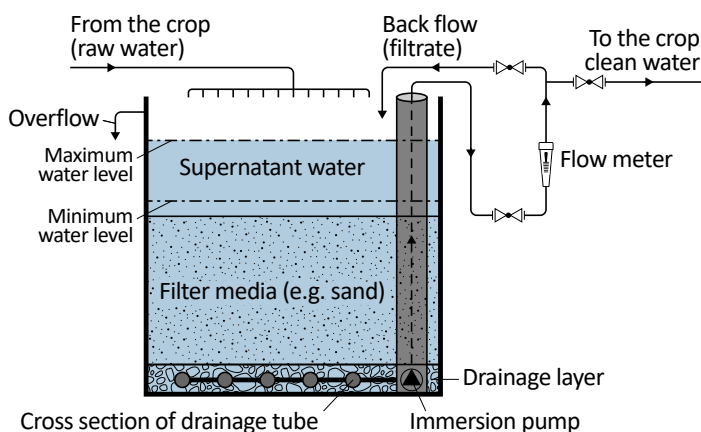


Figure 17A



Figure 17B

Figure 17. (A) Slow sand filtration system schematic. (B) Slow lava filtration system.

Source: (A) Ehret et al. 2001.

The maintenance of the biologically active Schmutzdecke is very important to the success of slow sand filters. It is recommended the water flow gently onto the filter so as not to damage the Schmutzdecke at the top layers. A flow rate of 10–30 cm per hour would allow a filter capacity of 100–300 L/m²/hr. These systems are thought of as ecosystems that need nutrients and the proper environment to survive and thrive. The slow flow rate of these systems is intentional to give enough time for the biological and chemical processes to happen. These reactions also require adequate oxygen levels (>3 mg/L) and optimal temperature (10–20°C).

While reducing pathogens, these systems promote the growth of beneficial microbes in the recycled water. Irrigation recirculation systems that use slow sand filtration are typically rich with bacteria (10³–10⁴ colony forming units per millilitre). This population of bacteria is thought to be beneficial for plants and reduces the ability of pathogens to colonize roots. However, a complete understanding of how these filters work is lacking.

Another important aspect of slow sand filters is sand grain size. Filtration is improved by using smaller grain sizes, similar to filter pore size mentioned in the previous section. Smaller grains have more surface area per unit volume of the filter bed which allows them to filter more water. The smaller the grain size the better it is at trapping organic and inorganic matter. High filtration efficacy occurs when using a fine and medium sand grain size between 0.15–0.8 mm. However, the smaller the grain size the lower the flow rate of water (again, similar to filter pore size mentioned in the previous section).

The biological and chemical activity of the Schmutzdecke, in combination with the physical filtration of the grains, has proven to be very effective at reducing pathogen loads

in recycled irrigation solutions. Studies have shown a reduction of Phytophthora, Pythium and viruses by 95–100% using this system. Modern systems that work on a similar concept to slow sand filters are known as biofilters or bioreactors (Figure 18).



Figure 18. Modern bioreactor.

Benefits of Slow Sand Filtration

- Maintains natural beneficial microbes in the recirculated water.
- A relatively simple, low-tech, low-cost filtration and disinfection system, requiring minimal energy and specialized training to maintain.
- No phytotoxic side effects have been observed when using slow sand filters.

Drawbacks of Slow Sand Filtration

- Slow flow rates do not allow slow sand filters to be used in operations that require large volumes of water.
- Slow sand filters require a significant amount of space to set up and this is accompanied by a large set-up cost.
- To prevent clogging, the Schmutzdecke needs to be partially removed every few weeks by scraping off the uppermost layers.
- Oxygen may be reduced in the solution due to consumption in the Schmutzdecke. Oxygen needs to be supplemented through aeration or active gas supplementation in the nutrient solution.
- Fluctuating temperatures may affect efficacy as metabolic activity is linked to temperature.

Heat (Pasteurization)

High temperatures disrupt cell integrity and interrupt metabolic processes in microorganisms (Figure 19). If you apply enough heat for a long time, all microorganisms will be destroyed. Both temperature and contact time is important for this process (dose = quantity and duration). The more heat you apply in a given period, the less contact time you need to kill pathogens. Conversely, if you reduce the heat applied in a given period, generally it will take longer to kill the pathogens. That is the premise behind using heat to disinfect recycled nutrient solution. These types of systems pass water through a series of heat exchangers until the target temperature and desired contact time is reached. The heat is then recovered to cool the water before being reapplied to the crop.

The quickest way to kill most microbes is to heat water to 95°C for 30 seconds. This is effective for controlling *Pythium* and

Phytophthora, as well as some viruses. To reduce energy costs, heat levels can be reduced to 60°C but the exposure time must be increased to 2 minutes to eliminate fungi, bacteria and nematodes. To kill viruses, water needs to be heated to at least 85°C for 3 minutes. It is recommended that water pH be reduced to 4.5 before heating to reduce calcium precipitation on metal heat exchange plates. Using corrosion-free materials (such as stainless steel) is also recommended.



Figure 19. Heat (Pasteurization) disinfection system (left) and clean and dirty water tanks (right).

Benefits of Pasteurizers

- High temperatures are effective at controlling many pathogens.

Drawbacks of Pasteurizers

- Heat, like most disinfection techniques, does not discriminate between beneficial microbes and pathogenic ones.
- High temperatures have some undesired effects such as the precipitation of some salts. These precipitates may cause clogging of the irrigation system and reduce the availability of these minerals to the crop.
- Heat reduces the amount of dissolved oxygen in the water, so oxygen supplementation through aeration or active injection may be necessary after heat treatment.

Ultraviolet (UV) Light

UV light is electromagnetic radiation with a wavelength between 100–400 nm. Germicidal UV lamps emit radiation that causes a photochemical reaction that damages the genetic material of microorganisms (DNA and RNA), reducing their ability to reproduce and grow. The optimum UV wavelength to kill microbes is around 254 nm. High pressure mercury lamps emit UV-C radiation with a wavelength between 200–280 nm whereas low pressure lamps emit around 254 nm. High pressure lamps are less energy efficient than low pressure lamps, but both are effective at controlling pathogens in recirculated nutrient solution, if the proper dose is reached (Figure 20).



Figure 20. UV disinfection system.

Similar to heat treatment, the efficacy of UV disinfection depends on the **dose** (quantity and duration) of the UV treatment. This is measured in millijoules per square centimetre (mJ/cm^2). The effective dose of UV can range from 28–850 mJ/cm^2 . A UV dose of 100 mJ/cm^2 is sufficient to eliminate pathogenic fungi, while a higher dose of 250 mJ/cm^2 is recommended to remove all organisms including viruses. An even higher dose of 500 mJ/cm^2 is required to achieve 96% mortality of some nematodes,

while 100 mJ/cm^2 prevents reproduction of other nematodes and reduces infection of plant roots. Some *Phytophthora* and *Pythium* species can be controlled with UV doses of as little as 17–88 mJ/cm^2 . In addition to dose, disinfection efficacy is also dependent on the flow rate of water past the UV source. The slower the water flow rate, the more exposure microbes have to the UV light, which increases mortality. But the most important factor affecting efficacy is water clarity. UV light is reflected off or absorbed by many materials in the water such as suspended solids or plant debris. These particles may shield microbes from the UV light and reduce mortality. Recycled water must be filtered prior to UV light treatment to remove suspended particles from the water. This increases UV light penetration and transmission. For UV light to effectively disinfect recycled irrigation water, a minimum UV transmission rate of 60% is essential: the water needs to be clear enough so that at least 60% of the UV light emitted by the lamp passes through the water and is not absorbed or reflected by particles. Iron (Fe) also absorbs in the UV waveband. Given the necessity of iron as a micronutrient it is often present or added to fertigation solutions and will impact the efficacy of UV treatments.

Benefits of UV

- UV light is not corrosive, does not depend on the pH of the solution and does not require additional chemicals.
- Can be combined with some other systems (e.g., ozone) as part of an advanced oxidation process.

Drawbacks of UV

- UV light, like heat treatment, does not discriminate between beneficial microbes and pathogens.
- Treating recycled nutrient solutions with high intensity UV has been shown

to inhibit growth of lettuce plants downstream of the treatment, potentially due to generation of ozone and/or free radicals that can harm plants.

- UV light can destroy some iron (Fe) chelates which can cause Fe to precipitate out of solution and coat the UV lamp, which will reduce the effective lamp output. Furthermore, Fe itself absorbs UV light, thereby reducing the number of photons available to inactivate pathogens. The lack of Fe in solution may result in Fe chlorosis if levels are not amended after treatment. However, some chelates perform better under UV treatment, preventing the negative effects of UV-induced Fe deficiency.
- UV light treatment can be costly, requiring frequent maintenance to clean and/or replace the lamps. UV lamps degrade relatively quickly with time, which results in reduced dose (up to 10% loss after 1000 hours of operation, and 35% loss after continuous operation for a year). UV lamps need to be monitored and changed as required.

Ozone (O₃)

Ozone is a very strong oxidizing agent. Oxidizing agents can cause damage to lipids, proteins and DNA. Ozone is more than 1.5 times stronger than chlorine. It acts by direct oxidation or through the production of short-lived hydroxyl free radicals and superoxide ions (bad stuff that can hurt living things). Ozone is generated by combining an oxygen atom (O⁻) with an oxygen molecule (O₂), two oxygen atoms bonded together, to form ozone (O₃) (Figure 21). As stated in the previous section, UV light can be used to generate ozone, but much higher concentrations are produced if electricity is used as the source of energy for this reaction. For example, corona discharge ozone generators use electricity to produce

ozone from air, whereas electrolytic ozone generators use electricity to produce ozone directly in water.



Figure 21. Ozone disinfection system.

Once ozone is generated it is relatively unstable and decomposes back to oxygen (O₂), or reacts with other materials, in a short period of time. It has a half-life of less than 20 minutes when dissolved in clean water. This instability can be a good thing and a bad thing. On the positive side, once ozone is produced in the recycled water it kills microbes and quickly breaks down. It is recommended to treat solutions until a minimum residual ozone concentration of approximately 0.5 mg per L is achieved and maintained for approximately 5 minutes. Prior to distribution to the crop, this residual will automatically degrade or can be easily stripped out with an ozone destruct filter. This said, there is evidence that suggests a small residual could be maintained during distribution to help keep pipes and emitters clean without any crop damage. Also, because ozone breaks down into oxygen,

it has the potential to dramatically increase dissolved oxygen levels. One negative aspect of ozone's short half-life is that it must be produced at the point of use and immediately dissolved in the solution.

Similar to heat and UV light treatment, the efficacy of ozone depends on the target microbe you're trying to kill and the **dose** (quantity and duration) of ozone. Most microorganisms of concern to producers are controlled if ozone is applied until a residual of approximately 0.5 mg/L can be maintained for 5 minutes in the bulk solution (i.e., in tank), but this can increase to 100 mg/L for 30 minutes for some viruses. Achieving this residual will require dramatically different amounts of ozone depending on the initial contamination level of the water.

Manganese (Mn), iron (Fe) and micronutrient chelates can be oxidized by ozone, and therefore compete with other contaminants/pathogens for applied ozone. This increases the ozone demand in the solution resulting in longer processing times.

Another important aspect of ozone disinfection systems is the size of the bubbles used by the system to infuse the ozone gas into the water. In general, smaller bubbles are more effective at killing microbes than bigger bubbles. This is because smaller bubbles come out of solution more slowly and generate more hydroxyl radicals when they burst or cavitate than bigger bubbles. For example, microbubbles (< 50 μm diameter) have been shown to kill microbes faster than millibubbles (mm-cm diameter). Now there are systems that can produce nanobubbles (nm diameter).

Benefits of ozone

- In addition to eliminating pathogens/microorganisms, ozone degrades pesticides and other contaminants in the solution.

- Ozone has a low environmental hazard due to its very short half-life in water.
- Ozone can increase overall dissolved oxygen levels as it reacts or reverts to oxygen.

Drawbacks of ozone

- Does not discriminate between beneficial microbes and pathogens.
- Ozone treatment systems have a high cost of installation and maintenance.
- High levels of ozone can be phytotoxic if the ozone does not break down fast enough before the recycled solution is reapplied to the crop.
- Ozone demand can be very high in water with a high pH, high organic matter, nitrite, manganese, iron or bicarbonate concentrations.
- Gaseous ozone is hazardous and proper training, handling and safety measures must be in place.
- Ozone is an aggressive oxidant and as such system components must be compatible (e.g., rubber fittings will rapidly disintegrate).

Multi-Stage Filtration and Disinfection

There is no single solution for water treatment; rather, a systems approach should be taken that deploys the appropriate water treatment technologies for the specific water quality needs of the operation. Many greenhouse producers install multiple filtration and disinfection systems that work in series. This ensures redundancy in their operations and gives them peace of mind that their recycled water is not harboring high levels of pathogens that can cause disease (Figure 22).

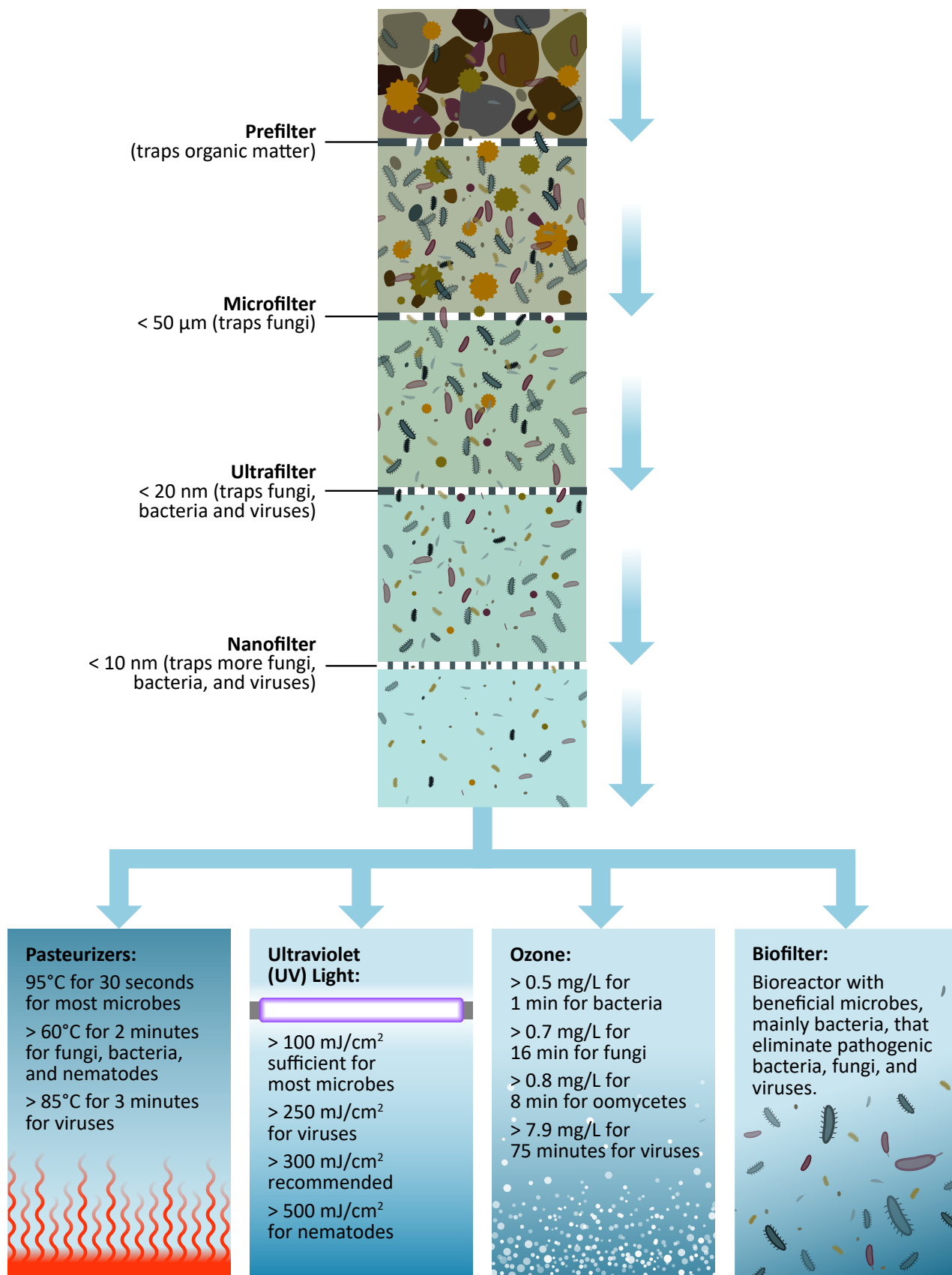


Figure 22. Multi-stage filtration and disinfection of recirculated water.

It is recommended that producers check the level of pathogens in their source water, their recycled water, and before and after filtration and disinfection on a regular basis to ensure that their filtration and disinfection systems are working as they should. Water samples can be sent to a number of accredited and certified laboratories in Ontario that offer identification and quantification services. These services may include molecular techniques that can identify a plethora of pathogens at once, like DNA multiscan or sequencing. However, positive results from molecular tests should be interpreted with caution because they mean that the genetic material (DNA or RNA) of a pathogen is present, but they cannot tell if that pathogen is alive or dead. If a pathogen is detected with a molecular test, it should be verified with bioassays (culturing or inoculation of test plants) to confirm the pathogen is alive.

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CHAPTER 8

Growing Media

The growing media must provide four basic needs for the plant: water, nutrients, oxygen and support for the roots. Most Ontario greenhouse vegetable producers have shifted from soil culture to soilless culture. Today, most greenhouse vegetables are grown in stone wool (55%) or coir (coco coir) (35%). The remaining 10% are grown in other media such as nutrient film technique (NFT), deep water culture (DWC), ponds, foam, expanded clay pellets, peat, sawdust and soil. Soilless media normally supply none or a limited amount of nutrients for plant growth, so these must be provided in the fertilizer solution. This application of fertilizer and water through an irrigation system is called **fertigation**.

Most vine crops (tomatoes, cucumbers, peppers and eggplants) require strong root support systems for the vine, so they are typically grown in slabs of soilless media that provide the strong base. More compact crops (leafy greens, lettuce) don't require a strong

root system and can be grown with their roots in smaller containers or shallow growing media on benches or directly in water using NFT, DWC or pond systems.

Adequate oxygen levels are necessary for proper respiration and energy production by the root system. Most soilless media, like stone wool, are porous enough to sustain proper oxygen levels. However, when roots are grown directly in water, like NFT, DWC or pond systems, dissolved oxygen (DO) levels must be monitored. DO levels should be maintained above 5 mg/L (parts per million (ppm)). Supersaturation of oxygen up to 20-30 ppm can prevent low oxygen stress, also known as hypoxia. Hypoxia can contribute to poor productivity and plant health and make the crop more susceptible to root diseases. However, too high of a DO can also negatively affect plant growth.

Stone Wool Culture

Stone wool is an artificial growing media made from basaltic rock, coke and limestone. The basaltic rock is melted in a kiln and

then spun in threads that are layered to form mats. Originally, these were used to insulate buildings and pipes, and now they are used to provide a growing medium for horticultural purposes. Horticultural stone wool is manufactured under strict guidelines to create a uniform product of specific density and treated with a wetting agent. It is cut to standard sizes and then wrapped and sealed in plastic (polyethylene) bags. Stone wool is available as slabs, blocks, starting plugs and granules. The granules are used either on their own or as an additive to peat bag culture to form peat wool. Granule bag culture is not as popular as slab stone wool culture.

Horticultural stone wool:

- is sterile (free of pathogens, weed seeds, etc.)
- has no or low cation-exchange capacity (is inert and therefore does not interact with the nutrient solution)
- has a high water-holding capacity
- usually has a high initial pH
- is lightweight and easy to handle
- allows for a shorter between-crop interval because it can be removed quickly

Stone wool is a free-draining media. It is important to lay out the production system to ensure uniform watering of all plants. If the system is not well designed (for example, if the slope of the greenhouse floor is uneven), some bags may remain too wet or too dry, restricting plant growth and fruit production and causing lack of uniformity in the crop.

A basic stone wool production system consists of:

- a groundsheet that isolates the soil surface from the greenhouse growing environment
- a raised trough system (with an integrated irrigation and leachate (drain) collection system)

- stone wool slabs that are placed on the troughs

If the system is set up directly on the ground, it should include:

- a groundsheet that isolates the soil surface from the greenhouse growing environment
- a polystyrene strip for insulation that is placed either above or below the groundsheet
- stone wool slabs that are placed on top of the polystyrene strip and groundsheet
- a drip irrigation delivery system
- a leachate collection system

Seed is sown in the stone wool starting plugs and, after germination, transplanted into stone wool blocks. Once they have reached the desired size and stage, plants in the stone wool blocks are transplanted onto the stone wool slabs in the greenhouse. This process can take up to 6–8 weeks for tomatoes, 3–4 weeks for cucumbers and 7–9 weeks for peppers. This period is longer during winter and shorter in summer.

Raised Trough System

The raised trough system is used in most new greenhouses, while many older facilities have been retrofitted to accommodate it (Figure 23). In this system, stone wool slabs are placed in preformed raised troughs, 80–120 cm off the ground, either on stands or hung off chains from the trusses of greenhouses engineered to hold this load. The trough contains an integrated irrigation and leachate collection system.

The raised trough system lends itself to intercropping, where the new crop is planted as the old crop is coming to an end. The final harvest of the old crop coincides with the first harvest of the new crop.



Figure 23. Raised trough system.

Advantages of raised trough systems

- Setup is faster during the construction phase, as there is no need to form the ground for leachate trenches.
- The greenhouse ground remains flat, making it easier to set up the pipe rail heating system or track system as well as perform greenhouse maintenance.
- The main fertigation tubing can be shaded easily to avoid heating by direct sunlight. This is important, otherwise the raised temperature can drastically reduce nutrient solution DO levels.
- The system is labour friendly, involving:
 - less bending
 - easier layout of growing media bags
 - easier planting
 - deleafing conducted at an easier working height
 - easier and faster harvesting.
- Pest and diseases can be better managed because:
 - the base of the plants and lower stems and leaves can be more easily monitored for diseases
 - better air circulation improves the microclimate around the plant and minimizes the incidence of disease

- dripper problems, such as blockages and leaks, are easier to detect and fix
- biocontrols can be more easily introduced at the base of plants.
- Water management in the growing media is easier because:
 - slabs are level, resulting in uniform wetness and draining
 - watering is more uniform, since all the emitters are uniformly placed and leaks and other problems are easily detected and repaired
 - the nutrient solution is easily collected for recirculation purposes.
- Cleanup during the season (such as plant clipping) is easier, as is end-of season crop removal.

Disadvantages of raised trough systems

- The troughs are costly.
- The greenhouse structure must be designed to hold the weight of the troughs and plants.
- Algae can grow in the drain channel.
- There is less flexibility to alternate crops.

Water Management

Stone wool slabs, although free draining, can become waterlogged if short, frequent irrigation cycles are applied or if the drainage holes are not cut properly to allow free drainage. Drainage is especially critical during early plant growth stages and under low light conditions. Set the bags up so they are level and uniformly spaced, and make sure the drainage holes are cut cleanly, sized and located correctly for optimum drainage.

After the bags are placed in the greenhouse, they are saturated with a complete nutrient solution. The bag must be completely saturated to activate the wetting agent, ensuring the whole slab is available to the

plant roots. After planting, cut a slit in the bag from the bottom up to allow for drainage. This is usually done 24–48 hours after planting. Water the plants for half an hour and then apply water only on sunny days over the next 2–3 days. This ensures rapid root penetration into the slab and allows the slab to dry out.



CAUTION

Overwatering may result in excess vegetative growth and plants that are more susceptible to disease.



CAUTION

The final degree of slab dryness depends on the characteristics of the slab purchased. Follow manufacturers' recommendations.

Subsequently, the frequency and quantity of water applied to the crop is determined by several factors:

- the stage of plant growth
- the size of the plant
- light levels
- temperatures in the greenhouse and in the slab
- relative humidity or vapour pressure deficit in the greenhouse
- the amount of air movement

In general, 100 mL/cycle is used. This may vary depending on:

- the type of stone wool
- the stage of plant growth
- the time of year
- electrical conductivity (EC), a measure of the quantity of total dissolved salts or total ions present in the solution
- percentage drain

To determine the correct watering pattern, monitor both the EC in the slab and the leachate. Also, monitor the percent leachate. A leachate of 20–30% is generally recommended.

The simplest way to manually measure percent leachate is to use a 4-L graduated container to collect the solution applied from a single emitter. Use a similar container to collect the leachate from four plants irrigated by the emitter. Compare the volumes. If they are the same, the rate of leaching was 25%. Alternatively, collect the solution from two emitters and the leachate from eight plants.

Keep a daily record of the amount of leachate and irrigation, as well as the EC and pH of the irrigation and the leachate. This helps in determining the irrigation strategy to follow. If the EC is rising, it indicates that not enough water was applied based on the prevailing conditions for that day. Conversely, if the EC is decreasing, it indicates that too much water was applied.

Night watering is usually not recommended. Start the irrigation cycles 1–2 hours after sunrise and end them 1–2 hours before sunset. After the first irrigation cycle, check the slabs for leachate. If there is leachate after the first cycle, the slabs are too wet. To shorten irrigation time, either delay the start-up time or end the irrigation earlier. If there is no leachate after the third cycle, the bags are too dry. In this case, extend the irrigation program later into the evening or start it earlier in the day.

An irrigation program that is not properly set up can decrease production and increase incidence of disease.

If the slabs are too wet, the result is:

- poor aeration of the slab
- softer, vegetative growth
- poor root growth

- increased risk of root disease

If the slabs are too dry, the result is:

- damaged root hairs
- high EC
- problems with calcium uptake and movement, leading to blossom end rot (BER) in tomatoes and peppers and leaf scorch/curl on young cucumber leaves
- harder growth and thinner plants
- smaller, darker, thicker leaves

To initiate and control the irrigation cycles control computers typically use either time, start tray, accumulated light radiation, water content meter or weigh scale or a combination of these.

The water content, EC and temperature of a stone wool slab may be measured using a unit available commercially. These units are portable and can measure data from several slabs at any time of day and night. The latest models are permanently installed and send recorded data directly to the irrigation computer, where adjustments to the irrigation schedule may be made.

Fertilizer Schedules

Most stone wool slabs tend to have a high pH when they are used for the first time. To compensate for this high pH, apply a nutrient solution with a pH of 5.0–5.5. It usually takes some time before the pH remains at the desired level of 5.5–6.5, depending on the crop. Since the stone wool slab is inert, always apply a complete nutrient solution.

Coir

Coir is a relatively new growing substrate in Ontario that has become popular over the past few years due to its competitive price and ease of disposal at the end of the cropping season. It is an organic substrate made of waste materials from the coconut

fibre industry. To create it, the long fibres from the coconut husk are removed and the remaining material is screened and graded. The result is spheres of various diameters with a high water-holding capacity, high porosity and medium-to-high cation-exchange capacity. The material has a pH of 5.6–6.5 and a bulk density of approximately 82 kilograms per metre cubed (kg/m³). After treatment to remove excess salts, the material is dried, compressed in cakes and packaged in plastic (polyethylene) bags before shipping.

It is used in a layout similar to stone wool production, with the following differences:

- Soak the bags with a nutrient solution that has a calcium level about 10% higher and a potassium level about 10% lower than the solution used for stone wool fertigation.
- Before placing plants, fully saturate the coir to allow the fibres to regain their natural state.
- If precut bags are used, be sure to saturate them completely.
- Adjust water management based on the characteristics of the coir.

The size, shape and uniformity of particles/fibres in the coir slab determine its water-holding capacity and the amount of water available to the plants. In some cases, the mix of particles produces a slab that leads to plants that are more generative, requiring more frequent watering, which is better for production when light levels are low. In other cases, the particle mix creates a slab that leads to plants that are more vegetative, requiring adjustments to the water regime to prevent overwatering. This variability exists from brand to brand and, in some cases, from bag to bag.

Coir re-wets easily and drains quickly, allowing easier steering of the plant. At the end of the cropping cycle, coir can be composted.

Nutrient Film Technique (NFT)

Nutrient film technique (NFT) is a method of growing plants in a continuous shallow flow of nutrient solution (Figure 24). This technique is a true hydroponic culture, where the bare roots of the plants are bathed in a nutrient solution that is recycled in a closed system. This saves both fertilizer and water and reduces the impact on the environment.



Figure 24. Nutrient film technique.

The basic design consists of a reservoir tank and components such as pumps, a solution delivery network, growing troughs and a solution return system. The nutrient solution is pumped from the reservoir to the top end of the growing trough, flowing by gravity to the return line and back to the reservoir. The growing trough is set on a slope of 1–2% to facilitate the flow of the nutrient solution.

Reservoir Tank

The reservoir tank for an NFT system is located below grade to allow for a gravity-fed return flow of the nutrient solution. The tank can be constructed in a variety of ways:

- concrete blocks assembled to form a tank
- concrete poured to form a tank
- concrete crocks (containers) buried in the ground, with a cement floor

- rigid plastic tanks buried in the ground or placed as inserts in concrete casings
- a pit with wooden walls lined with a swimming pool liner

If concrete is used, it must be painted with a rubber-based, non-phytotoxic (not harmful to the crop) paint to protect the concrete from the nutrient solution and to inhibit the ability of the concrete to raise the pH of the nutrient solution.

Reservoir tanks are usually designed to have a 5,500 L/0.5 ha capacity with 4,000–4,500 L of water in the tank. Meanwhile traditional NFT systems are designed to have approximately 13,500–13,750 L/0.5 ha of nutrient solution circulating in the greenhouse. Provisions should be made to store this water in case of electrical power failure. The tank is equipped with an automatic freshwater intake used to top it up with fresh water whenever the level in the tank drops below a set point.

Pump System

The pumping system must be able to deliver a high volume of water (at least 2 L/min/emitter) at a low pressure, be reliable and be equipped with stainless steel or plastic impellers and components. Normally, systems are designed with one 5-horse power (HP) pumping station per acre (0.4 ha). In this case, a standby 5-HP pump should also be installed and equipped with a sensor to automatically switch it on when required.

A more economical technique is to install three pumps of 2 HP each in parallel, all running at once. If one pump fails, the two remaining pumps are capable of supplying enough solution to the crop to minimize crop injury while repairs are conducted.

As a safety feature, keep a spare motor. Since electrical disruption can cause crop devastation, all facilities must have a standby electrical generator that can provide enough electricity to power the pumps and other

essential greenhouse equipment (e.g., heat, vents, computers, etc.).

An added benefit of using three 2-HP pumps in parallel is that the extra pumping capacity allows producers to increase the solution flow rate of 2 L/min/trough if required. The extra capacity can also be used to aerate the tanks or send the nutrient solution to the in-line monitoring system and to the heating and pasteurization systems. This removes the need for an extra pump to supply nutrient solution for these purposes.

pH and EC Controllers

The pH and EC of the nutrient solution is continuously monitored by in-line probes. If the reading varies from the set point established by the producer, the pH and EC controllers automatically trigger the attached nutrient solution dosing pumps. This system adds fertilizer, acids and bases on a continual basis as required. A time-out switch on the controllers prevents over-dosing. This is an important safety feature since excessive fertilizer or acid/base can harm the crop. As a safety measure, install a second set of pH and EC monitors as a check on the primary controllers.

A computerized fertilizer injector system can also be used to monitor and adjust the nutrient solution. The advantage of such a system is that it can:

- monitor several NFT reservoir tanks from a single unit
- maintain the integrity of the nutrient solutions for each NFT system
- allow for different feed schedules (e.g., older crops vs. younger crops) to be maintained in each system.

Temperature Control

The optimum solution temperature is 18–21°C. Usually the solution temperature reflects air temperature: as the air temperature increases

during the day, so does the temperature of the nutrient solution. Similarly, when the air temperature decreases at night, the nutrient solution temperature will also drop. An additional heating source is therefore necessary to maintain a constant solution temperature, especially when adding fresh water.

Stainless steel heating coils are placed in the reservoir tank or, more commonly, in a small auxiliary tank. The main pump delivers the nutrient solution to the auxiliary tank via a side loop. Once the solution is heated, it is allowed to return to the reservoir tank.

As the temperature of the nutrient solution increases, the dissolved oxygen in the nutrient solution decreases. This may become a problem in the summer, especially when planting a fall crop. Because the young plants initially do not provide adequate shade, the radiant energy from the sun heats up the nutrient solution. Temperatures as high as 30°C are not uncommon. Fresh water or chillers can be used to cool the nutrient solution.

Disinfection

A disinfection loop in the NFT system that siphons off 25% of the nutrient solution is used to partially disinfect the nutrient solution. Completely disinfecting the nutrient solution is not recommended because a sterile solution allows rapid proliferation of microbial populations. In contrast, a partial disinfection reduces the microbial population in the solution but doesn't eliminate it, creating a balance between beneficial and non-beneficial microbial populations.

Most producers install an ultraviolet (UV) disinfection system that allows 25% of the nutrient solution to pass through UV lamps and back into the reservoir tank. Ozonation is another method of disinfecting the nutrient solution. However, it requires special customized systems to avoid plant injury and

ensure efficiency. While slow sand filtration is an effective technique, it is not commonly used for NFT systems, since very large systems would be required to handle the volume of water and the flow rate necessary to effectively treat the nutrient solution.

Aeration

The nutrient solution must be aerated to ensure that the plants get enough oxygen for their root systems. Creating a large drop between the return line and the level of solution in the tank provides good agitation and helps replenish the oxygen. An aeration loop, using a venturi system, also improves oxygenation by forcing air into the nutrient solution. Injecting oxygen into the nutrient solution using ozone systems or bubble systems is another way to maintain adequate oxygen levels.

Example Plumbing for Nutrient Solution Distribution and Collection

The nutrient solution delivery system must be designed to ensure all troughs receive the same flow rate (2 L/min/trough) (Figure 25). A 75 mm main header from the pump set delivers the nutrient solution to a 37.5–50 mm subheader. The subheader then delivers the solution to a 19–25 mm sub-subheader at each zone, from which a 4-mm flexible tube delivers at least 2 L of nutrient solution per minute per trough. A well-designed system will require little or no balancing between zones to ensure even water distribution. Polyvinyl chloride (PVC) material is used for all plumbing components since the nutrient solution can corrode galvanized pipes, releasing zinc ions that may damage the crop.

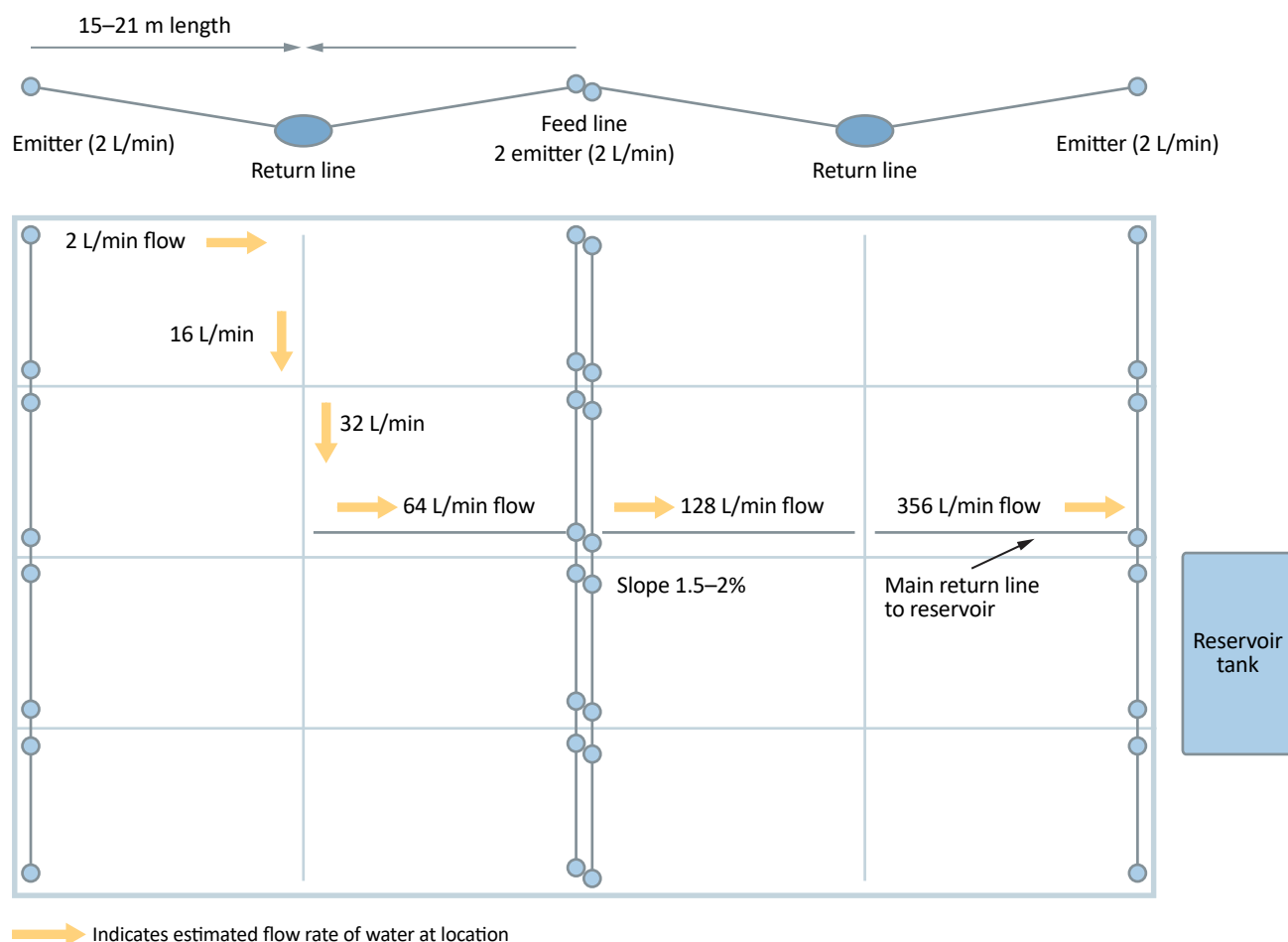


Figure 25. Example layout for nutrient film technique emitters and return line.

The intakes for the pumps are usually located near the bottom of the reservoir tank and require a basket filter with a one-way check valve at the bottom. This is crucial in case of a power failure, since these pumps do not need to be primed once the generator restores electricity.

The return line is buried in the ground and consists of 10 cm sewer pipe, which is durable, inexpensive and easy to install. Holes cut into the pipe, or "T" junctions located at every trough return location allow the solution to flow from the growing trough into the return line. The solution flows by gravity to the reservoir tank. A 0.5% slope is usually adequate. A large drop between the return line and the top of the nutrient solution is necessary to ensure maximum mixing of the return solution with the solution in the reservoir. The increased agitation enhances solution aeration, while extensions placed at the end of the return line may also increase agitation, further improving aeration. A coarse filter (e.g., a nylon stocking placed over the opening) will trap any root pieces or other material that may clog the pump impellers.

Growing Trough

Numerous types of troughs are available. These vary from aluminum troughs with plastic covers, to preformed rigid plastic troughs, with flaps to 6 mm white-on-black polytubes. In all cases, the purpose of the trough is to provide a channel for the nutrient solution to flow through and for the roots to grow in. The least expensive system is the 6 mm polytube laid on polystyrene that is 4 cm thick and 20 cm wide. A wide shallow groove, running along the length of the polystyrene, channels the nutrient solution towards the middle of the trough. This is especially important in the early stages of the cropping cycle to ensure all plants receive nutrient solution. However, too deep a channel results in poor aeration, decreasing the amount of oxygen available to the roots, which in turn decreases performance and encourages root die-back and diseases.

Ideally the trough should have a slope of 1.5–2%, be 15 m long and be 30 cm wide at the base. If the trough is longer than 21 m, modifications to the slope and flow rate must be made.

Phytotoxicity

It is important to ensure that all components of the NFT system are non-phytotoxic. Do not use metal components (galvanized pipes or copper pipes) because they corrode and release micronutrients, such as zinc or copper, that will accumulate to toxic levels. Plastic components in the irrigation lines, as well as the growing trough, must be non-phytotoxic. Components in some flexible plastics are extremely toxic to plants. Avoid using sodium (Na) and chloride (Cl) containing water and fertilizers, since they can easily increase Cl and Na to phytotoxic levels and the nutrient solution has to be disposed of more frequently.

Soil Culture

The number of producers using this medium has declined. However, organic and some smaller greenhouse operations continue to produce greenhouse vegetable crops using soil. Drip irrigation or tape irrigation is commonly used to grow soil crops in the greenhouse. Factors that need to be considered when using soil culture include: soil type, drainage, flooding and leaching, soil pasteurization, organic matter, pH control and drip irrigation.

Soil Type

To achieve maximum production, producers should have a well-aerated soil with good drainage that is rich in nutrients, high in organic matter content and free of pathogens. The most suitable soils are loam, sandy loam and some silty loam types. Other soil types may be used but require proper management and higher input costs to achieve maximum productivity. For example, early winter production in a heavy clay soil requires the

installation of tile drains, the addition of organic matter content before the cropping season to aggregate soil particles and careful water and nutrient management to achieve success. Sandy soils with poor water-holding capacity require frequent watering (with nutrients), which leads to increased potential for groundwater contamination. This problem can be overcome with a collection system designed to catch and recycle the excess water.

Drainage

A well-draining soil is best for greenhouse vegetable production. A tile drainage system installed in ground beds ensures all excess water is carried away. Contact a local agricultural drainage company to help design the system. Generally, 10 cm diameter tile set 35 cm deep and 45–60 cm apart with a slope of 10 cm in 150 m is adequate.

Flooding and Leaching

Prior to planting, the soil should be irrigated to bring it to field capacity. The amount of water required to do this varies depending upon the soil type and the soil moisture content at the time. In general, use 20–50 L/m². Water leaching (100 L/m²) may be necessary in some soils to lower high levels of ammonium and manganese, especially in soils that were steam pasteurized.

Soil Pasteurization

Harmful pathogens (bacteria and fungi) are present in most soils, along with weed seeds and insects. Soil pasteurization is a good control mechanism for pests and pathogens. Soils should be in fine tilth to allow rapid, uniform penetration of the steam or fumigant. Large clods or lumps of dirt and undecomposed crop remains (stems and roots) may hinder full penetration.

Under ideal conditions, heating the soil to 60°C for 30 minutes will eliminate most organisms of concern except viruses

(Table 13). Heating the soil above 82°C eliminates beneficial organisms as well and sterilizes the soil, making it vulnerable to a greater degree of infection than before.

Other undesirable side effects of over-heating are:

- excessive ammonia release
- manganese toxicity
- destruction of organic matter
- higher total salt level

Table 13. Time and Temperature Requirements to Destroy Weeds, Pests and Disease-Causing Organisms

Organism	Time (min.)	Temperature (°C)
Weeds (most)	15	70–80
Insects + mites	20	60–71
Bacteria (most)	10	60
<i>Fusarium</i>	30	57
<i>Botrytis</i>	15	55
<i>Nematodes</i>	15	55
<i>Rhizoctonia</i>	30	50
<i>Sclerotinia</i>	5	50
<i>Pythium</i>	40	46

Source: W.R. Jarvis. *Managing Diseases in Greenhouse Crops* (APS Press, 1992).

Greenhouse soils can be steam pasteurized by injecting steam through agricultural tile drain. Covering the soil surface with a plastic sheet to trap the steam in the soil greatly enhances the effectiveness of this process. Alternatively, if the drain tile is in disrepair, steam can be injected directly under a specially formulated plastic steam tarp by:

1

Burying the edges of the tarp in the soil, covering a 10–12 cm margin on each edge, so that when the steam is injected at a pressure of 41–48 kPa (6–7 psi), it does not escape.

2

Monitoring the temperature of the soil to ensure an adequate temperature has been achieved to pasteurize the soil without overheating it. Always leach the soil after steam pasteurization.

Chemical fumigants may also be used, although the choice is limited. Follow the manufacturer's label direction for rate, duration and venting periods to safely and effectively use these products.

Organic Matter

A high level of organic matter helps maintain a stable soil structure and improves the water-holding capacity and aeration of the soil. Coarse peat at rates as high as 500 m³/ha may be incorporated into new soils to improve their condition. Peat is acidic (pH 4.0) and therefore lowers the pH of the soil. This is a benefit for alkaline soils but must be corrected in acidic soils by adding lime (5 kg of limestone/m³ of peat).

The organic matter in greenhouse soils decomposes quite quickly, so apply 100 m³ of peat/ha each year. Incorporate both peat and lime in the soil prior to the main cultivation. Composted manure may be incorporated to increase organic matter content, but weed and herbicide contamination may cause severe crop losses.

pH Control

Greenhouse fruits and vegetables grow reasonably well within a wide range of soil pH levels (5.5–7.5), but a pH of 6.0–6.5 for mineral soils and 5.0–5.5 for organic soils is generally accepted as optimal. To raise the pH of the soil to the desired level, use either ground calcitic limestone (3 tonnes per hectare for each 0.5 pH unit increase for most light soils) or dolomitic limestone (if the soil magnesium level is low).

Adding peat to the soil for organic matter amendment lowers the pH of high-pH soils. Alternatively, soil pH can be reduced by adding elemental sulphur (flowers of sulphur) at 50–100 kg/ha for each 0.5–1.0 unit of pH decrease or apply ordinary sulphur to the soil and incorporate it into the top 15–30 cm of the soil. Do this several weeks before planting, keeping in mind that the reaction will be slow in cold soils. The amount of sulphur required varies between soils, depending on the buffering capacity (exchange capacity) and the original pH of the soil.

The pH of the soil around the plant roots is more critical than in the walkway. Adjusting the pH at the plant site can easily be accomplished through drip irrigation by adding phosphoric or nitric acid to a complete nutrient solution to achieve a pH of 5.5. This will maintain clean irrigation lines and drippers, as well as lower the pH around the rootzone, enhancing plant growth.

Drip Irrigation

A drip irrigation system:

- allows producers to regulate the amount of water and fertilizer reaching the crop
- reduces humidity of the greenhouse
- allows the use of white plastic (polyethylene) film as a light-reflecting mulch
- keeps the produce clean

The irrigation system is designed to deliver nutrient solution to each plant through a series of pipes with in-line emitters or hose-end drippers at 2 L/hr/plant. A nutrient solution containing all required fertilizers is applied 3–4 times/day to meet the water and nutrient needs of the plant. The type and quantity of fertilizer and the volume of water applied will depend on:

- the type of crop grown
- stage of crop
- time of the season

- light level
- temperature of the greenhouse
- water-holding capacity of the soil

Each day, evaluate the condition of the soil approximately 10 cm away from the plant and 10–15 cm below the surface to determine the beginning and length of the irrigation cycle. The pH and electrical conductivity (EC) measurements of this sample also help to indicate the nutrient status of the soil. A pH reading of 5.5–6.5 and an EC reading of 0.9–1.2 mS/cm is considered ideal. Information from these quick tests will assist in determining how much fertilizer and water the crop requires.

To set the required fertilizer schedule, it helps to have a laboratory soil analysis of a composite soil sample taken from several locations in the greenhouse. In the early stages of the cropping cycle, conduct this analysis weekly. Later in the cropping cycle, every 2–3 weeks is sufficient. More frequent testing may be necessary if crop production problems occur.

For organic production, the [Canadian Organic Standards](#) at the Canadian Food Inspection Agency should be consulted.

Integrated Rootzone Management (IRM)

The term **rootzone** is defined as the environment where roots reside in a soilless cultivation system. For plants growing in the aforementioned stone wool growing system, the rootzone includes both the stone wool block and the bag; for the NFT system, it's the entire nutrient solution in the trough. Regardless of which growing system (e.g., stone wool or NFT) is used, to maintain a healthy and productive crop it is essential to provide the plant rootzone with an environment that has adequate water, nutrients, dissolved oxygen (DO), optimal temperature and is free of plant pathogens.

All these elements in the rootzone are interconnected and they are influenced by other factors such as the growing environment. Changes to one element can affect the others. For example, watering too frequently or with too much quantity can cause rootzone oxygen deficiency, and insufficient fertigation can cause water and nutrient deficiencies. Oxygen deficiency can invite pathogens such as *Pythium* to cause pythium root rot. Watering decisions also depend on the growing media used, the plant development stage and the growing environment. When a porous medium is used, or when under high light levels, the plant needs to be watered more frequently, and visa versa. IRM takes into consideration all the factors which can influence rootzone elements (e.g., water, nutrient and DO), their relationships with each other and their relationships with the other factors such as the plant size and development stage, the microclimate and the growing media. Therefore, to provide the plant with an optimal rootzone an IRM approach is a must.

References

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CHAPTER 9

Supplemental Lighting for Winter Production

The market demand for locally grown fruits and vegetables year-round has driven adoption of lighting technologies for winter food production in greenhouses and vertical farms in Ontario. Here, we review some of the lighting research conducted at Agriculture and Agri-Food Canada's Harrow Research and Development Centre (Harrow, Ontario) over the past several years. Generalized recommendations for light intensity, **photoperiod** and **daily light integral (DLI)** are summarized in [Table 15](#) for practical commercial greenhouse production using overhead lighting, high pressure sodium (HPS), light-emitting diodes (LED) or a hybrid system of HPS and LED. This section also highlights studies conducted in Harrow to test different combinations of overhead, inter-lighting and dynamic long photoperiod, low intensity lighting recipes for winter production of cucumbers, tomatoes, peppers

and microgreens. You will find detailed information about the light recipes used in the studies and their results. Overall, the inclusion of LED inter-lighting with overhead HPS lighting boosted early production numbers in cucumbers and small doses of far-red light with HPS lighting or LEDs benefited winter tomato and pepper production. Dynamic light recipes for long photoperiods (up to 24 hours) for greenhouse production of tomatoes, cucumbers and peppers in the winter and microgreens in vertical farms were also identified. The next step is to incorporate the information gained from dynamic long photoperiod lighting research into dynamic lighting control programs to significantly reduce light fixture costs and energy costs.

Background

The impressive growth of Ontario's fruit and vegetable greenhouse sector over the past decade or so would not have been possible without advancements in lighting research and technologies. More efficient light fixtures, such as LED and new double-ended HPS lights, have allowed producers to extend their

growing seasons into the dark winter months in an economically sustainable way. The ability of LED lights to be adjusted to different light intensities and light spectral outputs was a game-changer. This allowed producers and researchers to experiment with different light recipes to optimize the light environment for their crops.

Before the commercialization of LED lights, HPS lights were used as only overhead lights for vegetable greenhouse production because the high operating temperature of HPS light bulbs did not allow them to be used close to the canopy. HPS lights also only provided one spectral output that was

not adjustable. LED lights changed all that. The lower operating temperature of LED lights allowed them to be used not only as overhead lights, but also as inter-lighting within the canopy of vine crops like tomato, cucumber and peppers (Figure 26). Also, by adjusting the spectral output of LEDs it became much easier to manipulate canopy architecture, and this allowed crops that were not able to grow well under HPS lights to grow under LED lights.

The difference in efficacy of light fixtures is another important consideration for your operation. LED lights are typically more efficacious than HPS lights (Table 14).

Table 14. Typical Energy Input of Light Fixtures to Achieve 220 $\mu\text{mol}/\text{m}^2/\text{sec}$ of Photosynthetically Active Radiation (PAR)

Light Fixture	Fixture Efficacy ($\mu\text{mol}/\text{J}$)	Electricity Consumption (W/m^2)	Annual Electricity Consumption (MJ/m^2) 2000 Hours	Annual Electricity Consumption (MJ/m^2) 2500 Hours
New double ended HPS	1.7	129.4	931.8	1164.7
Broad spectrum white LED	2.7	81.5	586.7	733.3
LED with high red	3.4	64.7	465.9	582.4
Red LED	4.0	55.0	396.0	495.0

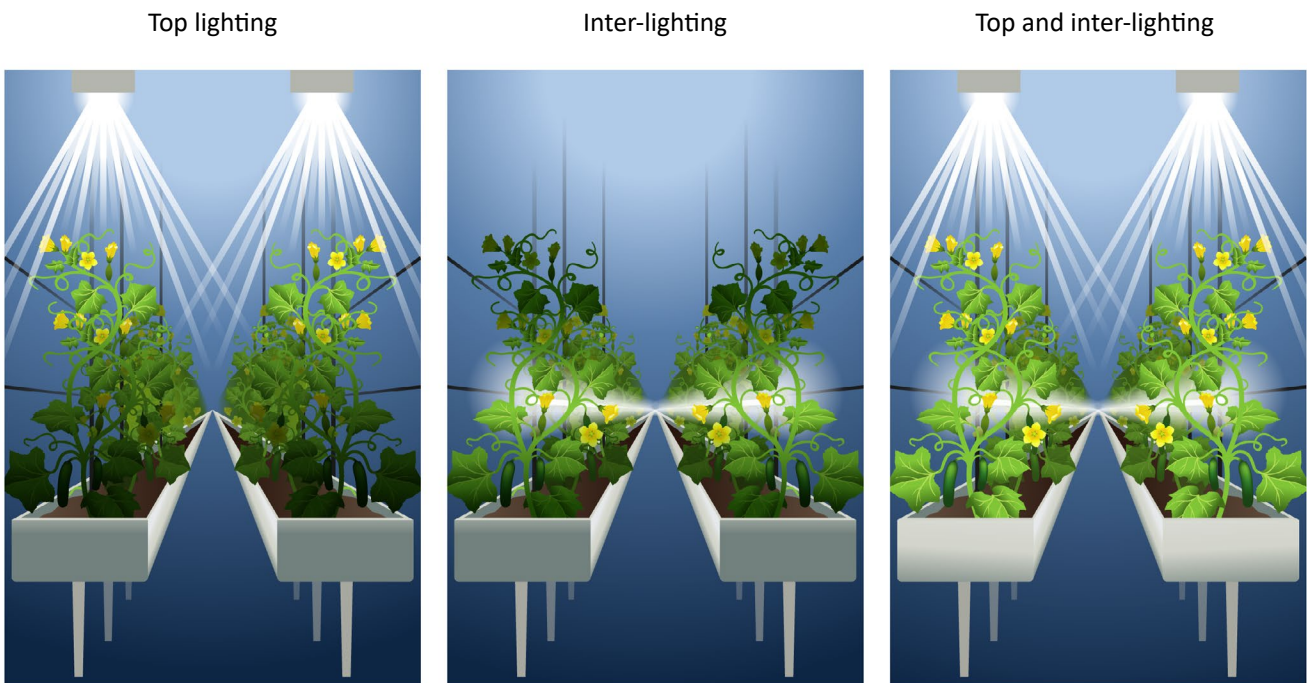


Figure 26. Supplemental light distribution.

The efficacy of a fixture when producing photosynthetically active radiation (PAR, 400–700 nm) is measured in the number of photons (μmol) per joule (J) of electricity it consumes. The higher the number of $\mu\text{mol}/\text{J}$ for a fixture, the more light it produces per joule and the more efficacious it is. The efficacy of HPS lights ranges from 0.9–1.8 $\mu\text{mol}/\text{J}$ depending on the type, whereas the efficacy of LED lights typically ranges from 2.0–4.0 $\mu\text{mol}/\text{J}$. This means that in most cases LED lights use less energy than HPS lights.

Growing greenhouse fruits and vegetables in the winter using supplemental lighting is not as easy as flicking on a switch. Producers also need to adjust:

- cultivar selection
- crop schedule
- plant density
- training systems
- climate control
- irrigation schedule

The most obvious change is cropping schedule. Non-lit greenhouse vegetable production of high wire tomatoes, peppers and cucumbers typically starts with planting around December and January and harvesting ends around October and November for cleanout. Growing these crops in the winter or for year-round production using supplemental lighting typically starts with planting around September and October and harvesting ends the following July or August.

In addition to changing the cropping schedule, the climate controls and irrigation schedules must be adjusted for winter production under lights to reflect the three periods with different light conditions when there is:

- natural daylight only or daylight plus artificial light

- artificial light only
- dark nighttime

Irrigation should start when the supplemental lighting is turned on, which is typically a few hours before sunrise. Supplemental lights should be turned off around one hour before sunset to allow pollinating bees to return to their hives, otherwise they might get disoriented by the artificial light.

Cultivar selection also changes when growing with supplemental lighting. Many greenhouse vegetable cultivars suitable for non-lit production may not be suitable for winter production under supplemental lighting. The type of supplemental lighting also affects cultivar selection. For example, HPS lights may cause faster senescence in generative cultivars, while LED lights may delay fruit production in vigorous cultivars.

When designing a lighting strategy for tall greenhouse vegetables, there are four main components that producers should think about:

1

Light Intensity — What intensity of light should be used? This is usually called the photosynthetic photon flux density (PPFD) and it measures the amount of PAR light that plants are receiving in micromoles (μmol) per metre squared (m^2) per second.

2

Photoperiod — What photoperiod should be used? The photoperiod is the length of time there is light whether it is sunlight or artificial light, and it is typically measured in hours. When you multiply the light intensity ($\text{mol}/\text{m}^2/\text{hour}$) by the photoperiod (in hours) you get the daily light integral (DLI). This is the total accumulated amount of light that plants are receiving in one day measured in moles ($\text{mol}/\text{m}^2/\text{day}$).

3

Light Spectrum – Which light spectrum should be used? This is the light quality or light colour produced by the light fixtures measured in nanometres (nm). Broad spectrum white light typically covers the PAR spectrum (400–700 nm), blue light is 400–500 nm, green/yellow/amber light is 500–600 nm, red light is 600–700 nm and far-red light is 700–800 nm.

4

Light Distribution – What vertical distribution of light should be used? Lights can be used as top lighting above the canopy, inter-lighting within the canopy or a combination of both. As mentioned earlier, HPS and LED lights can be used in different ways.

The general standard light intensity, photoperiod and DLI values used today for winter production of high wire tomato, cucumber and peppers are shown in [Table 15](#). Please note these values vary with cultivar, local climate and light fixture.

Since 2002, much of the lighting research that helped advance Ontario's vegetable greenhouse industry was conducted by scientists at Agriculture and Agri-Food Canada's Harrow Research and Development Centre in collaboration with other research institutions. This section aims to highlight and summarize the vegetable greenhouse lighting research conducted in Harrow since 2012. Each of the sections below includes

information specific to a different greenhouse crop (cucumbers, tomatoes and peppers), information about the light recipes used by the researchers and the results of the trials. The last section includes information about dynamic lighting research that was conducted on multiple crops (tomatoes, cucumbers, peppers and microgreens). The dynamic lighting research will allow producers to truly take advantage of the flexibility in the output offered by LED technology and the variation in electricity market price to reduce energy costs.

Mini-Cucumbers, Overhead HPS, and Inter-lighting LED Lights

Some of the earliest vegetable lighting trials in Harrow were published by Hao et al. in 2012 and 2015. These trials were conducted on mini-cucumbers. The first set of trials investigated combined HPS overhead lighting with LED inter-lighting systems ([Figure 27](#)).



Figure 27. LED inter-lighting for mini-cucumbers. *Source:* Agriculture and Agri-Food Canada.

Table 15. Implementation of Supplemental Lighting in Winter Greenhouse Vegetable Production

Crop	Intensity ($\mu\text{mol}/\text{m}^2/\text{sec}$)	Photoperiod (hours)	Practical DLI ($\text{mol}/\text{m}^2/\text{day}$) ¹	DLI for the highest yield ($\text{mol}/\text{m}^2/\text{day}$) ²
Cucumber	200–250	16–20	~20	>30
Tomato	200–250	16–18	~20	>30
Pepper	100–200	13–16	~16	>20

¹ This is the total DLI (sunlight + supplemental light) normally used in commercial production to maintain good production. Higher DLIs may further increase yield but not necessarily higher profits because the additional yield gain may not justify the additional input costs.

² This is the total DLI to achieve the highest yield.

Lighting Recipes (Table 16)

The crop was grown under 145 $\mu\text{mol}/\text{m}^2/\text{sec}$ of HPS overhead lighting in combination with 14.5 $\mu\text{mol}/\text{m}^2/\text{sec}$ of LED inter-lighting (10% of top light). Red (660 nm), blue (460 nm) and white (broad spectrum 400–700 nm) inter-lighting fixtures were tested to determine the best colour. The photoperiod varied between 12 and 20 hours depending on natural light conditions. Supplemental lighting periods increased as the crop aged, from 12 hours per day the week after planting to 20 hours per day when a full canopy had developed. The inter-lighting was placed 60 cm above the raised growing trough close to the harvesting fruit.

The second set of trials focused on optimizing the combination of HPS overhead lighting and red/blue inter-lighting by testing different overhead intensities (120 and 165 $\mu\text{mol}/\text{m}^2/\text{sec}$) and different intensities of inter-lighting (one or two rows of red/blue LED producing 36.7 $\mu\text{mol}/\text{m}^2/\text{sec}$ of light for each fixture). These trials also tested different planting densities (2.8 and 3.6 plants/ m^2) to determine if plant density affected the response to inter-lighting. The HPS top lights were placed 3 m from the ground and the LED inter-lighting was placed at mid-height of the crop canopy. When there were two inter-lighting modules included, one was placed about 60 cm above the bottom edge of the crop canopy and the other module was placed 40 cm above the bottom module. Together the two modules provided 73.4 $\mu\text{mol}/\text{m}^2/\text{sec}$ of red/blue light. The photoperiod varied between 9 and 20 hours and the supplemental lighting periods increased with crop age in a similar way to the first set of experiments. The supplemental lighting always ended just before sunset. The longer photoperiods were achieved by starting the lighting earlier in the night such as at 11:00 p.m. for the 18-hour photoperiod.

Table 16. Light Test Recipes for Mini-Cucumbers with Overhead HPS and LED Inter-Lighting

Factors	Test Recipe 1	Test Recipe 2
Lighting Fixtures	Top HPS LED inter-lighting	Top HPS LED inter-lighting
LED Colour	Red (660 nm) Blue (460 nm) White (400–700)	Red/Blue
Intensity ($\mu\text{mol}/\text{m}^2/\text{sec}$)	HPS–145 LED–14.5 (10% of HPS)	HPS–120 or 165 LED–36.7 (one or two fixtures)
Photo-period (h)	12 hrs after planting increased to 20 hrs at full canopy	12 hrs after planting increased to 20 hrs at full canopy

Results

In the first set of experiments, plants with blue LED inter-lighting were taller than plants with no inter-lighting under HPS overhead lights. Plants exposed to red and white LED inter-lighting treatments had more leaves than plants with no inter-lighting. Red, blue and white LED inter-lighting all improved fruit visual quality and increased yield more than 10% in early production. However, yield improvements associated with LED inter-lighting were not as significant during late production periods.

In the second set of experiments, without HPS top lighting, single LED inter-lighting increased marketable fruit weight by 32% over the control without any supplemental lighting. The combination of HPS overhead lights and LED inter-lighting once again increased yield and fruit quality over HPS overhead lights alone. In combination with the less intense HPS top lighting the double rows of LED inter-lighting increased marketable fruit weight by 42% over the top lighting alone. The single LED inter-lighting and the more intense HPS top lighting increased marketable fruit weight by 10% over the top lighting alone and the mini-cucumbers were greener. Best results with low intensity top lighting and inter-lighting were realized when lower plant density was used. In contrast, higher plant density showed the best results with higher intensity top lighting and inter-lighting.

Tomatoes, HPS and Far-Red Light

One of the first studies on far-red light in Harrow was published by Hao et al. in 2016. It investigated the effect of adding far-red light (725–750 nm) on tomato plants grown under HPS lights (Figure 28).



Figure 28. Tomato plants under HPS lights.
Source: Agriculture and Agri-Food Canada.

Lighting Recipes (Table 17)

Tomato plants grown under HPS lights with $165 \mu\text{mol}/\text{m}^2/\text{sec}$ were provided with four far-red intensity treatments (0, 8, 16 and $24 \mu\text{mol}/\text{m}^2/\text{sec}$). The photoperiod started at 1:00 a.m. and lasted until 5:00 p.m. in December, 5:20 p.m. in January, 6:02 p.m. in February and 7:10 p.m. in March. All lights were shut off when outside solar radiation was more than 300 W per m^2 .

Table 17. Light Test Recipes for Tomatoes with Overhead HPS and LED Inter-Lighting

Factors	Test Recipes
Lighting Fixtures	Top HPS Top LED
LED Colour	Far-Red (725–750 nm)
Intensity ($\mu\text{mol}/\text{m}^2/\text{sec}$)	HPS–165 LED–0, 8, 16, and 24
Photoperiod (h)	Dec – 16 hrs (1:00 a.m. to 5:00 p.m.) Jan – $16 \frac{1}{3}$ hrs (1:00 a.m. to 5:20 p.m.) Feb – ~17 hrs (1:00 a.m. to 6:02 p.m.) Mar – ~18 hrs (1:00 a.m. to 7:10 p.m.) No lights when sunlight $> 300 \text{ W m}^{-2}$

Results

Supplemental far-red light provided benefits in the early growth period during the winter when natural far-red light was low. The internode length and the chlorophyll content of young leaves increased with higher intensity of supplemental far-red light. Yield and size of the tomato plants also increased significantly, by as much as 6% for marketable fruit, with far-red light treatments in the first month of the trial (January to February). Far-red light also changed the fruit quality by increasing total carotenoid content of the fruit. The benefits of far-red light, however, did not persist into the later growth periods in March when there was more natural far-red light.

Overall, the low dose of far-red light ($8 \mu\text{mol}/\text{m}^2/\text{sec}$) achieved similar fruit yield as the higher doses and used less electricity and had lower capital and installation costs. This intensity is lower than the far-red light intensity mentioned in the pepper section below because these HPS lights had about 10% far-red light or about $17 \mu\text{mol}/\text{m}^2/\text{sec}$ in addition to the far-red LED treatments.

Peppers, HPS, LED and Far-Red Light

Hao et al. (2019) presented data from experiments on the effect of far-red light on bell pepper plants conducted between November 2017 and June 2018 (Figure 29).



Figure 29. Pepper plants with short internodes.
Source: Agriculture and Agri-Food Canada.

Lighting Recipes (Table 18)

Plants were grown under 200 $\mu\text{mol}/\text{m}^2/\text{sec}$ of:

1. HPS
2. HPS and LED hybrid
3. white LED
4. red/blue LED lights

An 18-hour photoperiod was used, and the lights were off when outside solar radiation was more than 300 W/m^2 . Each of these overhead light treatments also included 0, 26 or 52 $\mu\text{mol}/\text{m}^2/\text{sec}$ of far-red light. Without supplemental far-red light, the HPS lights already produced some far-red light whereas the LED lights did not.

Table 18. Light Test Recipes for Peppers with HPS, LED and Far-Red Light

Factors	Test Recipes
Lighting Fixtures	Top HPS Top HPS-LED hybrid
LED Colour	White (400–700 nm) Red/Blue Far-Red (725–750)
Intensity ($\mu\text{mol}/\text{m}^2/\text{sec}$)	HPS–200 LED–0, 26, 52
Photoperiod (h)	18 No lights when sunlight > 300 W/m^2

Results

Pepper plants grown under white LED lights were the tallest (12–15% more) and had the least amount of leaf chlorosis (73–90% less). Those grown under red/blue LED lights were the shortest with moderate leaf chlorosis, whereas the plants grown under HPS lights had the most leaf chlorosis and moderate height, as compared to the other treatments. Adding far-red light increased the height of plants grown under all the lights by 3–7%, except the plants grown under white LED lights which were already tall. Far-red light also increased yield by 4–14% under all lighting treatments, except for red/blue LED lights with the low far-red dose. Unlike tomatoes, these yield increases were observed throughout winter production.

Dynamic, Long Photoperiod, Low Intensity Lighting of Tomatoes, Mini-Cucumbers, Peppers and Microgreens

Yield increases from supplemental lighting are mostly determined by the added DLI, as summarized by the simplified saying of “1% of light increase = 1% yield increase.” The required DLI can be met over a shorter period of time with higher intensity lighting or a longer period of time with lower intensity lighting. Using a longer photoperiod with

lower intensity lighting can significantly reduce light fixture costs in comparison to a shorter photoperiod and higher light intensity, because less lights would need to be installed. Furthermore, in regions such as Ontario with large fluctuations in electricity prices at different times of the day, longer photoperiods allow much more flexibility to use cheaper electricity to meet the target DLI thereby significantly reducing electricity costs. However, plants have a biological clock and need “sleep,” just like humans. If the photoperiod is longer than certain thresholds, such as 16–17 hours for tomatoes, it will lead to leaf injury and yield reduction. This is known as photoperiod injury (Figure 30). In order to extend the photoperiod for greenhouse crops without photoperiod injury, we need to first find ways to overcome the crop’s biological clock to allow normal or better plant growth and development.



Figure 30. Tomato leaves with photoperiod injury. Source: Agriculture and Agri-Food Canada.

In recent years the research in Harrow has focused on testing various lighting recipes under longer photoperiods (up to 24 hours) and reduced intensities of light to find ways to overcome photoperiod injury. This was done using dynamic lights that were able to produce different light spectrums at different intensities at different times of the day.

Tomato 24-hour Dynamic Light Recipes and Results

The first successful 24-hour light trial conducted by scientists in Harrow was published by Lanoue et al. in 2019. It examined tomato greenhouse production under 24 hours of supplemental lighting using :

- alternating red light (200 $\mu\text{mol}/\text{m}^2/\text{sec}$ from 6:00 a.m. to 6:00 p.m.) and
- blue light (50 $\mu\text{mol}/\text{m}^2/\text{sec}$ from 6:00 p.m. to 6:00 a.m.).

This was compared to a 12-hour lighting photoperiod with red and blue lights:

- red at 200 $\mu\text{mol}/\text{m}^2/\text{sec}$ plus blue at 50 $\mu\text{mol}/\text{m}^2/\text{sec}$ from 6:00 a.m. to 6:00 p.m.

Lighting was applied from November to May. The supplemental lighting remained on regardless of sunlight radiation levels to ensure both treatments received the same total DLI (Figure 31).

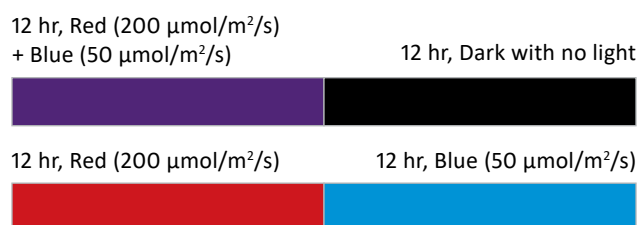


Figure 31. Tomato 24-hour dynamic light test recipes.

Plants grown under 24-hour lighting grew in a similar manner to those under 12 hours of light, but they produced 12% more leaf area and 10% more stem fresh weight. Plants under both light recipes also produced similar numbers of fruit, but the fruit produced by plants grown under 24-hour light weighed 15% more than the fruit produced by plants under the 12-hour light recipe. However, these differences were only seen in the early weeks of the experiment. Plants grown under both light recipes were similar later in the growing season.

Mini-Cucumber 24-hour Dynamic Lighting Recipes and Results

Another study published in 2021 by Lanoue et al. investigated production of mini-cucumbers under 24-hour lighting. There were four treatments:

- 1 16 hours (6:00 a.m. to 10:00 p.m.) of red light ($149 \mu\text{mol}/\text{m}^2/\text{sec}$) plus blue light ($25 \mu\text{mol}/\text{m}^2/\text{sec}$)
- 2 24 hours of red light ($96 \mu\text{mol}/\text{m}^2/\text{sec}$) plus blue light ($17 \mu\text{mol}/\text{m}^2/\text{sec}$)
- 3 24 hours of alternating red light ($151 \mu\text{mol}/\text{m}^2/\text{sec}$ for 16 hours, 6:00 a.m. to 10:00 p.m.) followed by blue light ($40 \mu\text{mol}/\text{m}^2/\text{sec}$ for 8 hours, 10:00 p.m. to 6:00 a.m.)
- 4 24 hours of alternating between red light ($210 \mu\text{mol}/\text{m}^2/\text{sec}$ for 12 hours, 6:00 a.m. to 6:00 p.m.) followed by blue light ($31 \mu\text{mol}/\text{m}^2/\text{sec}$ for 12 hours, 6:00 p.m. to 6:00 a.m.).

All treatments had the same DLI of $10 \text{ mol}/\text{m}^2/\text{day}$. Lighting began in November and the lights remained on regardless of solar radiation to ensure all lighting treatments had the same DLI (Figure 32).

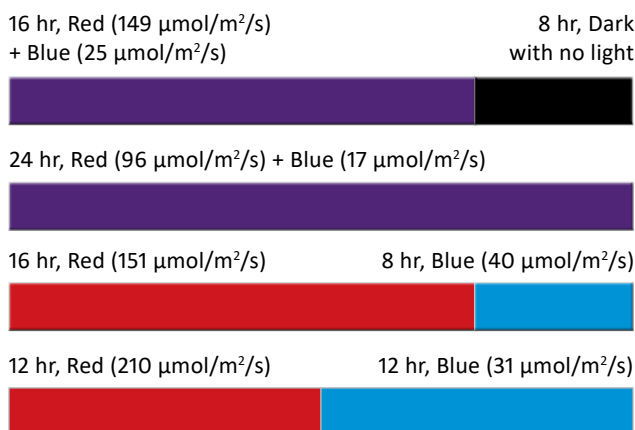


Figure 32. Mini-cucumber dynamic 24-hour light test recipes.

All plants grown under 24-hour lighting had higher chlorophyll content in their leaves compared to the 16-hour photoperiod treatment, but no other differences in growth or yield were observed between the treatments. However, the 24-hour lighting regimes had an economic advantage over the shorter period of lighting in achieving the same DLI with less light fixtures and shifting some electricity demand to overnight hours when prices are typically low in Ontario.

Pepper 24-hour Dynamic Lighting Recipes and Results

A paper published by Lanoue et al, 2022a, investigated the use of far-red light in a 24-hour lighting recipe for bell pepper plants. Five treatments were included:

- 1 16 hours of white light (broad spectrum, 400–700 nm)
- 2 24 hours of white light
- 3 24 hours alternating between white light (for 16 hours) followed by blue light (400–500 nm for 8 hours)
- 4 24 hours alternating between white light (for 16 hours) followed by blue light and far-red light (700–800 nm for 8 hours)
- 5 24 hours alternating between white light (for 16 hours) followed by far-red light (for 8 hours)

Two experiments were conducted with the above treatments. The first experiment had a PAR DLI of 13 mol/m²/day and far-red DLI of 1.3-1.5 mol/m²/day and the

second experiment had a PAR DLI of 10–11 mol/m²/day and a far-red DLI of 1.0–1.1 mol/m²/day (Table 19), (Figure 33).

Table 19. Daytime/Nighttime Light Colour, Intensity and DLI for 16- and 24-Hour Lighting Treatments on Peppers¹

Legend: n/a = Not Applicable

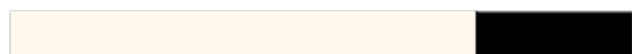
Lighting Type	Intensity/DLI	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
Experiment 1						
PAR	Daytime Intensity	220 (white)	147 (white)	181 (white)	180 (white)	n/a
PAR	Nighttime Intensity	0	147 (white)	75 (blue)	74 (blue)	n/a
PAR	DLI	13	13	13	13	n/a
Far-Red	Daytime Intensity	24	17	22	18	n/a
Far-Red	Nighttime Intensity	0	17	0	16	n/a
Far-Red	DLI	1.4	1.5	1.3	1.5	n/a
Experiment 2						
PAR	Daytime Intensity	180 (white)	121 (white)	153 (white)	153 (white)	183 (white)
PAR	Nighttime Intensity	0	121 (white)	55 (blue)	56 (blue)	0
PAR	DLI	10	10	10	10	11
Far-Red	Daytime Intensity	19	13	18	13	13
Far-Red	Nighttime Intensity	0	13	0	11	10
Far-Red	DLI	1.1	1.1	1.0	1.1	1.0

¹ All light intensity values were measured in $\mu\text{mol}/\text{m}^2/\text{sec}$ and the DLI numbers were in mol per m² per day.

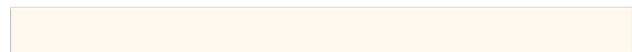
A. Experiment 1

16 hr, White (220 $\mu\text{mol}/\text{m}^2/\text{s}$)
+ FR (24 $\mu\text{mol}/\text{m}^2/\text{s}$)

8 hr, Dark
with no light

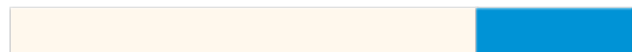


24 hr, White (147 $\mu\text{mol}/\text{m}^2/\text{s}$) + FR (17 $\mu\text{mol}/\text{m}^2/\text{s}$)



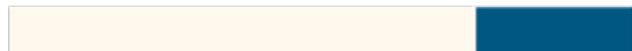
16 hr, White (181 $\mu\text{mol}/\text{m}^2/\text{s}$)
+ FR (22 $\mu\text{mol}/\text{m}^2/\text{s}$)

8 hr, Blue (73 $\mu\text{mol}/\text{m}^2/\text{s}$)



16 hr, White (180 $\mu\text{mol}/\text{m}^2/\text{s}$)
+ FR (18 $\mu\text{mol}/\text{m}^2/\text{s}$)

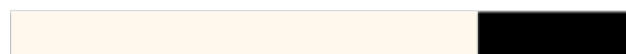
8 hr, Blue (74 $\mu\text{mol}/\text{m}^2/\text{s}$)
+ FR (16 $\mu\text{mol}/\text{m}^2/\text{s}$)



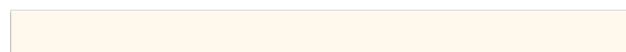
B. Experiment 2

16 hr, White (180 $\mu\text{mol}/\text{m}^2/\text{s}$)
+ FR (18 $\mu\text{mol}/\text{m}^2/\text{s}$)

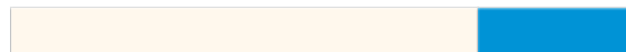
8 hr, Dark
with no light



24 hr, White (121 $\mu\text{mol}/\text{m}^2/\text{s}$) + FR (13 $\mu\text{mol}/\text{m}^2/\text{s}$)

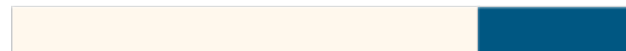


16 hr, White (153 $\mu\text{mol}/\text{m}^2/\text{s}$) + 8 hr, Blue (55 $\mu\text{mol}/\text{m}^2/\text{s}$)



16 hr, White (153 $\mu\text{mol}/\text{m}^2/\text{s}$)
+ FR (13 $\mu\text{mol}/\text{m}^2/\text{s}$)

8 hr, Blue (56 $\mu\text{mol}/\text{m}^2/\text{s}$)
+ FR (11 $\mu\text{mol}/\text{m}^2/\text{s}$)



16 hr, White (183 $\mu\text{mol}/\text{m}^2/\text{s}$)
+ FR (13 $\mu\text{mol}/\text{m}^2/\text{s}$)

8 hr, FR (10 $\mu\text{mol}/\text{m}^2/\text{s}$)

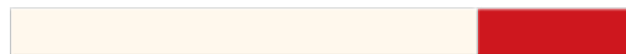


Figure 33. Pepper dynamic lighting and far-red (A) Experiment 1, and (B) Experiment 2 test recipes.

Fruit yield and fruit size was similar in all treatments, except for plants under 24 hours of white light that had lower fruit numbers and fruit weight than all other treatments. Both lighting treatments that included nighttime far-red light resulted in improved canopy architecture with 54-63% taller plants and increased internode length, which prevented fruit stacking (Figure 34). This was observed consistently in early and late production periods.



Figure 34. Fruit stacking in pepper plants with short internodes.

Source: Agriculture and Agri-Food Canada.

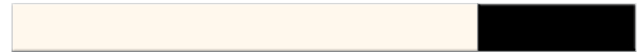
Microgreen 24-hour Dynamic Lighting Recipes and Results

In another recent publication by Lanoue et al, 2022b, investigated the effect of 24-hour white light on the growth of four types of microgreens: amaranth, collard greens, green basil and purple basil. These experiments were conducted in growth chambers, so they apply more to vertical farmers than greenhouse producers. Some seedlings

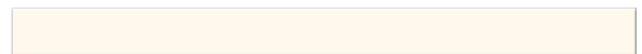
were exposed to a DLI of 14-15 mol/m²/day under 16 hours of light (251 μmol/m²/sec) or 24 hours of light (167 μmol/m²/sec), while other seedlings were exposed to a higher DLI of 21-22 mol/m²/day under 16 hours of light (377 μmol/m²/sec) or 24 hours of light (248 μmol/m²/sec) (Figure 35).

DLI = 14-15 moles/m²/day

16 hr, White (251 μmol/m²/s) 8 hr, Dark with no light

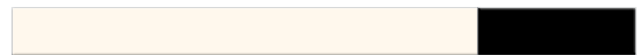


24 hr, White (167 μmol/m²/s)



DLI = 21-22 moles/m²/day

16 hr, White (377 μmol/m²/s) 8 hr, Dark with no light



24 hr, White (248 μmol/m²/s)

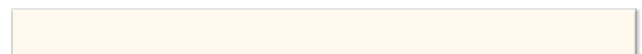


Figure 35. Microgreen 24-hour dynamic lighting test recipes.

Increases in yield (fresh weight) were observed for all microgreens including a 93% increase in amaranth, 46% increase in purple basil, 43% increase in green basil and a 21% yield increase in collard greens when the photoperiod was extended from 16 hours to 24 hours using the same light intensity. Food quality, as measured by antioxidant, phenolic, anthocyanin and chlorophyll content, was generally not affected or increased under 24 hours of lighting. Furthermore, the electricity cost per unit of fresh biomass was reduced by 8-38% in all microgreens when they were grown under 24-hour lighting because some electricity demands were shifted from more expensive on-peak daytime hours to cheaper off-peak nighttime hours.

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CHAPTER 10

Greenhouse Energy

Energy is one of the biggest expenses in greenhouse vegetable production. The judicious use of energy conservation technology is recommended for commercial greenhouses. However, the impact of this technology on crop production must be considered. Simply maintaining a lower 24-hour temperature is not advisable, since it decreases plant development, leads to lower fruit quality and increases the incidence of disease. Instead, it is better to optimize the growing conditions for maximum economic yield.

Greenhouse cover material greatly impacts energy use. Energy-saving double polyethylene (poly) greenhouses and/or double-walled acrylic side walls are common in Ontario. Management and cultural practices have changed to compensate for the lower light transmission and the lower rate of air exchange per hour of these greenhouses without reducing crop production. Natural air exchange in a glass house is 0.75–1.5 exchanges per hour,

while double poly greenhouses have 0.2–1.0 exchanges per hour. Keep in mind that newer greenhouses (both double poly and glass ones) have significantly less infiltration loss than older ones: 0.5–1 air exchanges per hour compared to 1–4 air exchanges per hour. In all greenhouses, natural exchange (and therefore heat loss) increases with age: poly film and sealing around glass should be kept in good repair.

New developments in greenhouse poly films have improved energy savings. Infrared (IR) films and anti-condensate films are examples. The IR films decrease heat loss from the greenhouse, while anti-condensate films reduce the need for venting to manage the greenhouse environment. As well, there is little accumulation of water on the inside roof surface with anti-condensate films, so light transmission is increased.

Other energy conservation techniques to implement include:

- installation and use of energy and/or light abatement curtains

- insulation of heating pipes to reduce heat loss along the mainline and headers during transportation from the boiler room
- side wall and foundation insulation — insulate at least 0.6 m below grade
- wind breaks — sheltering the greenhouse from prevailing winds will decrease infiltration losses
- heating system tune-ups that include regular boiler maintenance
- heat placement — locate heat pipes close to plants to decrease losses to greenhouse surfaces and locate grow pipes (small-diameter hot-water heating pipes) within the crop canopy to improve plant productivity/quality
- delay planting (in extreme cases) — plant when heating requirements are not as high, but keep in mind that early crops tend to command a higher market price

Energy/shade screens or curtains are used in all glass houses. In some cases, two sets of curtains are installed with one screen having high energy savings factor and the second with shading characteristics to assist in summer climate management. There is an increase in the number of double poly greenhouses with energy curtain installations.

In situations where artificial lights are installed it is good practice (and in some municipalities mandatory) to use light abatement curtains to prevent offsite light emissions. These light abatement curtains can decrease energy losses as well but must be integrated into the growing strategy to ensure sufficient humidity and temperature control. For more information see [Managing Nighttime Greenhouse Light Emissions](#) on [ONGreenhouseVegetables.ca](#) or [Effect of Greenhouse Light Abatement Curtains](#) on [Ontario.ca](#).

When starting crops during the winter (December to February), a temporary 2 mm clear polyethylene sheet can be placed over

the crop wires to seal the greenhouse to decrease energy loss and improve humidity in the greenhouse. The screen is removed once the plants' respiration rate releases excess moisture into the greenhouse.

Greenhouse Heating

For a greenhouse, the hourly and yearly heating requirement can be calculated based on inside and outside temperatures, the type of glazing material and the surface area of the greenhouse. Greenhouse heating companies will design systems suitable for local conditions. The standard heating system capacity recommendation for a 35°C temperature differential is 350 watts of heat energy per square metre of space (W/m²) for a glass greenhouse and 270 W/m² for a double-poly greenhouse.

Temperature requirements of major greenhouse vegetable crops (i.e., tomatoes, cucumbers, peppers and lettuce) vary significantly. Although some crops (e.g., lettuce) require less heat than others, heat requirements for a high-temperature crop should usually be considered in the design of the heating system so producers can easily switch crops, if they wish.

Central heating systems are the most common heating systems used in Ontario greenhouses. The source of energy is usually natural gas, with some producers using wood chips (waste wood) or pelletized fuel composed of wood, purpose-grown crops or agricultural residues. Bunker oil and #2 fuel oil may be used as a standby. In regions where natural gas supply is not available producers use propane. More recent advances in boiler technology have provided producers with the option of installing electric boilers or electric/natural gas hybrid boilers. This allows producers to use electricity to heat their greenhouse which may be equal to or cheaper than the price of natural gas at certain times of the day in Ontario, while reducing their greenhouse gas emissions.

With central heat systems, the heat is provided in the form of steam or hot water that is produced by a centrally located boiler and distributed through a system of heating pipes. The main advantage of this system is that the pipes can be located in the perimeter, where the greatest heat losses occur or within the crop where it is most efficient to heat the crop. Newer greenhouses opt for the hot water heating system because they can use their boilers during the day to produce CO₂ for enrichment and the hot water can be stored in insulated tanks for later use at night (Figure 36).



Figure 36. Hot water storage tanks.

The greatest benefit of hot water systems is the ability to regulate the temperature of the water within the pipes, which are located within the crop to help maintain good air movement around the plants. They can also be used as a pipe rail system for battery/ electric-powered carts that improve labour

efficiency. Grow pipes (small-diameter pipes located 50 cm above the growing row within the crop canopy) improve energy efficiency and decrease disease incidence (Figure 37).



Figure 37. Grow pipe located at maturing fruit.

Gas-fired unit heaters are an alternative to a central heating system. Although economical to install, these systems have several major drawbacks:

- poor temperature distribution
- greater temperature fluctuations
- lower seasonal combustion efficiency
- the possibility that gases from the flue may enter the greenhouse

Some producers have attached ductwork to the units to direct the warm air between the plant rows via large poly tubes. This greatly improves heat distribution.

Greenhouse Cooling

Greenhouses require a great deal of heat to maintain temperatures during the winter. In the warmer months, however, it is necessary to reduce temperatures. Producers often apply a coating on the exterior of their greenhouses, also known as whitewash, in the spring and summer that limits the amount of infrared radiation entering the greenhouse. This not only reduces the heat entering the

greenhouse but also causes some reduction in the intensity of sunlight (that can be detrimental in the summer).

Cooling is normally accomplished by exchanging greenhouse air with outside air. One air exchange per minute is typically required for high-temperature summer conditions with direct sunlight. The most common cooling method is natural ventilation: opening peak vents for glass and acrylic houses and newer designs of double poly greenhouses; opening gutter vents for older double poly designs.

In these passive systems, air exchange depends on ambient winds outside the greenhouse. If circulation fans are used to ensure uniform conditions within the greenhouse, these can also assist in mixing incoming air. Some growers use insect screens across vent openings: these reduce entry of insects and other pests into the greenhouse, at the cost of some reduction of air flow through the vents. Forced-air ventilation involves adding ventilation fans to actively exchange outside and greenhouse air to ensure air exchange occurs even in low wind conditions. With forced-air ventilation, additional summer cooling can be achieved by installing a fan and pad system that cause evaporative cooling. Some producers use high-pressure misting systems for both spring and summer cooling and for humidity control in the winter and spring. In Ontario, fruit and vegetable greenhouses generally do not use refrigeration-based air conditioners or central cooling facilities.

Temperature Sensing and Control

Producers typically use a range of electronic sensors measuring temperature, humidity, carbon dioxide, light levels and other operating parameters to track and maintain optimal growing conditions. These sensors

are often used in conjunction with digital industrial controllers or centralized control computers.

As technology improves, more sensors may be used in greenhouses, increasing data points to make more accurate decisions. Sensors for crop monitoring should be placed near the growing point of the plant canopy and then raised as the plant grows to monitor the temperature immediately around the growing point. Infrared temperature sensors to measure leaf temperatures provide more accurate information about plant conditions that allows for finer tuning of the greenhouse environment to improve efficiencies. If possible, deploy sensors at multiple locations since temperatures often vary in different parts of the greenhouse. Direct sunlight or stagnant conditions can cause sensors to give readings that are not representative of the greenhouse environment. For temperature and humidity measurement, use an aspirated boxed sensor to draw greenhouse air across the sensor and provide more accurate temperature readings.

Climate control computers are commonly used in modern greenhouse operations to control the interior environment and are programmed to adjust or maintain temperatures based on several factors including:

- the time of day
- intensity of sunlight
- relative humidity (RH)

In addition to a static temperature set point, the computer allows for increasing the temperature from night to day (and vice versa). This controlled increase or decrease in temperature enables producers to create an optimum temperature profile for plant growth, tailored to a selected cultivar or style of growing and prevailing external conditions. The climate control computer software programs allow the control of

many components of the greenhouse (boilers, vents, shade curtains, lighting, etc.) to maintain interior conditions. This provides growers with opportunities to make customized adjustments that are suitable to maximize productivity and maintain energy efficiency. These computers and associated sensor networks require an extensive initial investment. However, the improved control over temperature, RH and greenhouse climate helps minimize disease incidence, making computers essential for all greenhouse sizes.



Plant Raising

A proper start is essential to obtain a uniform, high-yielding crop that produces a good-quality product. A poor start results in an undesirable finish, requiring extra work to obtain a good crop and lower returns. There are three critical phases involved in raising plants (which may include grafting):

- 1 seed
- 2 sowing and germination
- 3 raising transplants to a finished product

Most greenhouse producers send their seed to propagators that specialize in germinating, grafting and starting transplants before seedlings are sent back to the production greenhouses for the season. This chapter provides information for producers who choose to propagate their own seedlings.

Seed

Use seed of the highest quality to ensure a good start. Most seed supplied to the greenhouse vegetable sector has been cleaned, treated and tested for germination/viability. This information is usually printed on the package or is available from the seed supplier. The germination test is conducted by a certified seed laboratory and performed according to strict, standardized guidelines. Germination is defined as the emergence of the radicle from the seed coat. In most cases, the percent germination will be 75–90% for tomatoes, 95% for cucumber, 85–95% for peppers and 95% for lettuce. Thus, the number of seeds ordered must be adjusted accordingly.

To the producer or plant raiser, a more critical value is the percent emergence, defined as the ratio of the number of seedlings that emerge from the growing media to the number of seeds sown. Emergence is influenced by numerous factors including:

- seed vigour
- depth of sowing

- moisture level in the media
- media aeration
- media temperature

The difference between percent germination and percent emergence may vary as much as 10%–20%.

Note that rate of seed germination varies dramatically; some seeds germinate very rapidly, while others are slower. Seeds can be grouped into three categories based on germination. The percentage in each category varies with species, cultivar and seed quality and fluctuates yearly.

Category I
Seeds emerge 2–3 days after sowing.

Category II
Seeds emerge 3–4 days after Category I seed.

Category III
Seeds emerge 3–4 days after Category II seed and have twisted cotyledons, or blind shoots, etc.

Categories I and II are true emergence and only these should be transplanted. Sow 25% more seeds than the number of plants required (Table 20). This will provide some additional high-quality plants that can be used to compensate for loss due to handling, etc.

Sowing and Germination

Sowing seed is a simple but critical step of plant raising. Ideally, producers should use a media with good drainage, water-holding capacity and aeration, such as stone wool plugs. These are available in various sizes, either in polystyrene trays or plastic flats.

Place seeds on the dimpled surface or in the hole of the plug and cover them with medium vermiculite. An even sowing depth is essential to ensure uniform emergence and seedling development. Seeds placed too deep in the growing media may take 2–3 days longer to emerge and may be weaker and slower to develop true leaves. Meanwhile, a seed placed on the surface is prone to drying out. In some cases, the radicle may not anchor properly, causing seedlings to fall over.

Prior to sowing, pre-soak the growing media with clear water or a dilute complete nutrient solution (electrical conductivity (EC) 1.0–1.5 mS/cm) at 20–25°C. After sowing, gently water the growing media to dampen the vermiculite. Ideally, place the flats/trays in a germination chamber or on benches with heating supplied either under the flat or under the bench. Cover the flats on the benches with a 2 mm clear plastic sheet to prevent them from drying out (Figure 38). To ensure uniform, rapid emergence, maintain the ideal media temperature specified in Table 20.

Table 20. Seed Requirements and Ideal Germination Media Temperature

Crop	# Plants Needed	# Seeds Ordered	Growing Media Temperature (°C)
Tomato	10,000	12,000–13,000	25
Cucumber	6,500	7,500 ¹	27
Pepper	10,000	12,000–13,000	26
Lettuce	1,000	1,100–1,200	16–18

¹ Cucumber seed, in general, has a higher percent germination and emergence.



Figure 38. Setup for seed germination.

After 60–75% emergence occurs, remove the flats/trays from the germination chamber or take off the plastic cover. This is usually done 50–96 hours after seeding, depending on the type of crop and cultivar grown. If this step is carried out too early, the emergence of Categories II and III seeds will be delayed. If it is carried out too late, it will result in the stretching of the Category I seedlings that have already emerged. Once maximum emergence — more than 80% — occurs, gradually lower the air temperature to 19–20°C for tomatoes, 21°C for cucumbers and 20°C for peppers. In most cases, a drop of 1°C per day is ideal. Adjust temperatures according to light levels to obtain the plant at the desired time. Too large a fluctuation between day and night temperatures results in elongated plants.

Once the true leaves emerge, water the flats with a complete nutrient solution, starting at an EC of 1.0 mS/cm and gradually raising the EC to about 3.0 mS/cm prior to transplanting. Overwatering results in poor aeration of the media, limiting root development. Also, excess moisture (especially applied as a mist) causes the rootzone temperature to drop, delaying growth and increasing variability between the plants. If the media is too dry, plant growth slows, leaves tend to be smaller and the EC of the media increases. The weaker plants may not survive or, if they do, will be more prone to disease.

Transplant seedlings into stone wool blocks/cubes once they reach the desired size. Too long a period in the flats (more than 21 days for tomatoes and peppers, 10 days for cucumbers) results in overcrowding, stretching and weakening of the seedlings.

Enriching with carbon dioxide (CO₂) and high-pressure sodium light, improve growth and help establish good roots. Keep the following guidelines in mind:

- Under good light conditions, enrich CO₂ to 1,000 ppm. Because seedlings are extremely sensitive, it is essential to use a clean CO₂ source, such as liquid CO₂.
- Using supplementary high-pressure sodium light (40 W/m²) enhances seedling development. Use an 18-hour photoperiod for tomatoes, peppers and lettuce and a 24-hour photoperiod for cucumbers.

Transplant Raising

Seedlings are ready to transplant when the first true leaves have fully emerged and/or when the seedlings touch one another. On average, tomatoes are ready to transplant 14–21 days after sowing; cucumbers, 7–10 days after sowing; and peppers, 14–21 days after sowing.

However, this varies depending on:

- cultivar
- seedling vigour
- light
- temperature
- nutrition
- moisture

A short, sturdy seedling is desirable. Ideally, seedlings should have a thick stem, dark-green leaves and a well-developed root system filling the plug. Before removing the plugs, soak the trays with nutrient solution to

allow the plugs to easily slide out of the tray. Handle the seedlings carefully. The stem may be very brittle and may snap when handled, or it may be soft and easily damaged. Pop the seedlings out of the tray using a plug popper. Handle seedlings by the cotyledons.

To prepare the stone wool blocks for the transplants, soak them with a complete nutrient solution (EC 2.0 mS/cm, pH 5.8) by immersing the blocks in a tub filled with the nutrient solution or by overhead watering. It is important to soak the blocks thoroughly and uniformly to ensure proper seedling establishment. Dry blocks restrict root development and growth, increasing plant-to-plant variability.

Place seedling plugs in holes in the blocks. A common practice used for tomatoes, and increasingly for peppers as well, is to fold the lower part of the stem into the hole and push the root plug down to fill the hole. Roots will develop along the stem within the hole, anchoring the seedling and keeping the cotyledonary leaves closer to the surface of the stone wool block. This technique results in a sturdier transplant which can aid in future lowering of the plant, but it requires seedlings that are soft and easily manipulated.

Place the transplants in trays (4–8 blocks/standard flat) that are then placed on heated benches or on a heated concrete floor. Alternatively, place the transplants directly on the floor (ebb and flood system) at 24–36 plants/m² (Figure 39). Transplants are ready for planting directly onto the stone wool slab, growing media bag or nutrient film technique (NFT) troughs in the main production area when:

- tomatoes — the first flowers are showing
- cucumbers — 4–5 true leaves are visible
- peppers — the flower at the first branching level is opening

Note

Roots must be well developed in the block and not overcrowded to allow for rapid penetration into the growing media once plants are placed in the production facility.



Figure 39. Transplant raising.

If needed, support the plants using a thin bamboo stake 20–30 cm long. This encourages development of larger transplants that are more easily handled and allows more time before plants need to be tied after transplanting.

Alternatively, new transplants can be moved directly into the production houses. Place the blocks on the stone wool slab beside the hole and place the drippers in the block. Use the irrigation system to water the blocks. This method saves on labour but increases heating costs, since the whole greenhouse operation must be heated.

After transplanting, maintain the greenhouse temperature at 23–25°C, 24 hours per day for 3–4 days and then gradually lower the temperature. In a starter house, using supplementary lighting (40 watts/m²) and CO₂ (1,000 ppm) increases the rate of root and shoot growth, resulting in earlier flower bud development. Keep a photoperiod of 18 hours for peppers and tomatoes and 24 hours for cucumbers. If plants are placed directly into the main production greenhouse, supplementary light is not effective but

additional CO₂ is beneficial. Use 1,000 ppm on sunny days and 400–500 ppm on cloudy days.

Irrigate transplants with a complete nutrient solution. Start at a low EC (2 mS/cm) and gradually increase it by 0.25 mS/cm/day up to 3 mS/cm, similar to the regime for emerged seedlings. In order to maintain a controlled growth, increase the EC further if:

- the rate of plant growth is too fast
- the available light is low
- the temperature in the greenhouse is low
- the relative humidity (RH) is high
- the moisture in the block is high

When to Water

Water in a timely manner and ensure leaves are not wet for extended periods of time, especially later in the day. Use either overhead watering or sub-irrigation. To determine when to water, use the weight method:

1 Weigh several blocks with transplants when saturated to establish a baseline.

2 Monitor the weight of several blocks daily.

3 When the average block weighs 50% less than the saturated weight, begin watering.

4 When watering, ensure the blocks are re-saturated.

Transplants placed directly in the production greenhouse require more frequent watering because the lower relative humidity in the greenhouse means that they lose water from the surface of the block as well as through transpiration. Night watering may be necessary on cold nights when the humidity in the greenhouse is low.

Grafting

Grafting desired cultivars onto rootstocks with stronger root systems is common practice. Grafting information is provided by the seed companies. Tomatoes and eggplants are grafted more frequently than cucumbers and peppers. A desirable cultivar (scion) is attached to a rootstock selected for its strong root system with higher disease resistance.

Grafting is used to:

- overcome shortcomings in the disease tolerance/resistance of the desired cultivar
- improve plant vigour and performance over a wider range of greenhouse climates and rootzone conditions

The following procedures will increase the likelihood of successful grafts:

- Sow rootstock seed 4–10 days before sowing the desired cultivar. This difference will depend on the rootstock used.
- After true leaves begin to emerge (about 14–15 days after sowing), lower the temperature for 2–3 days to strengthen the stems (Figure 40A).
- Designate an area specifically for grafting that can be isolated. All surfaces should be sterilized. Minimize cross-traffic of workers to reduce the risk of contamination.
- Cut the rootstock at a 45-degree angle below the cotyledon leaves using a sharp razor blade (Figure 40B).
- Place the grafting clip at the cut surface of the rootstock (Figure 40C).
- Similarly, cut the desired cultivar above the cotyledon leaves at a 45-degree angle. Make sure the scion is approximately the same diameter as the rootstock. Next, slip the scion into the clip attached to the rootstock (Figure 40D). Align the cuts to match so that the cut surfaces are touching. Cuts must match to ensure success (Figure 40E, Figure 40F, Figure 41).

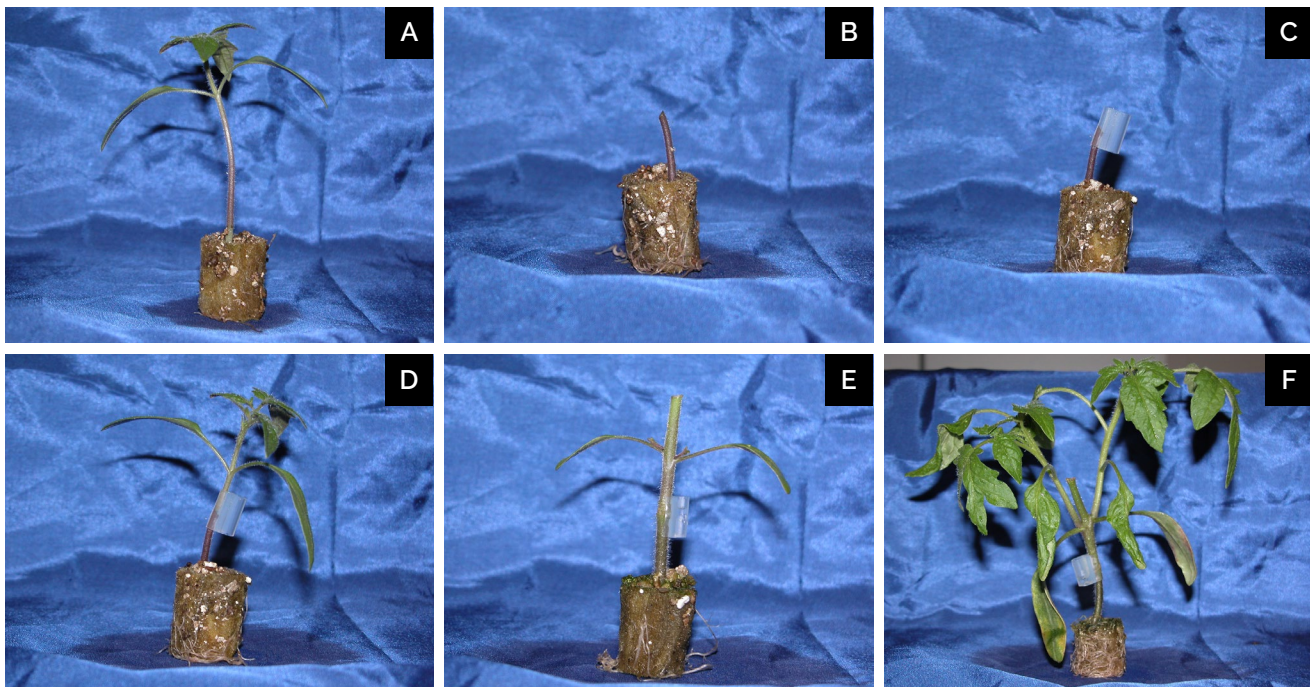


Figure 40. (A) Rootstock ready for grafting, (B) Rootstock with top removed. (C) Rootstock with clip added, (D) Scion placed in clip, (E) Finished graft topped at cotyledon leaf (F) Finished graft with two stems ready to transplant.

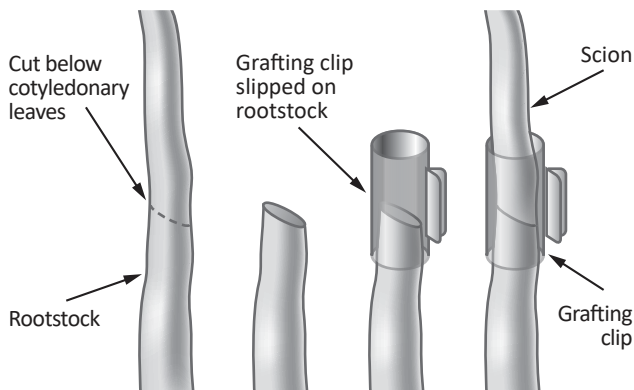


Figure 41. Japanese top grafting.

Note

Conduct this process in an aseptic environment and maintain a sterile work area and sterile equipment at all times. Do not delay the grafting process once started, because the loss of moisture from the cut surfaces will delay the knitting of the two stems.

After grafting:

- Place grafted seedlings in a chamber or a tent-like structure in the greenhouse where light, temperature and humidity are controlled to minimize water loss from the grafted seedlings and to promote rapid knitting of the rootstock to the top.
- After 3–4 days, gradually acclimatize the grafted seedlings to ambient conditions over a period of 3–4 days.
- Transplant the seedlings into blocks 10–12 days after grafting.
- Use normal transplant-raising techniques to grow the plants. Once the plants reach the desired height and development stage, transplant them into the production area.

Grafted plants tend to be vigorous and must be grown in conditions that promote generative plants, see [Chapter 1, Vegetative or Generative Plants](#) for more information. Without generative conditions, the first set may have misshapen flowers and small or poor-quality fruit or, in a worst-case scenario, aborted flowers.



CHAPTER 12

Nutrients and Analytic Testing

Since soilless cultivation systems (SCS) have a relatively low buffer capacity, all nutrients applied to the media are generally available to the crop (Table 23). This means that producers using SCS for greenhouse vegetables must use precision in applying fertilizers to their crops. Any errors in fertilization will show up relatively quickly in the plants. Fortunately, the plants will respond rapidly when the errors are corrected. While producers can use on-site colorimetric kits and single-element testing units to check some macronutrients more regularly, laboratory tests are more accurate.

Most nutrients are immobile because they move passively with water in the xylem. Some nutrients, such as nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg), are mobile because the plant actively moves them with sugars in the phloem. Immobile nutrients are transported to leaf tips and fruits by the pull of water transpiration and they reach lower parts of the plant more easily

than upper parts of the plants. Therefore, their deficiency symptoms usually appear in the upper parts of the plant first. Mobile nutrients, on the other hand, are actively moved with sugars to the upper growing regions of the plant. Therefore, their deficiency symptoms usually appear in the lower parts of the plant first (Figure 42).

Nutrient Solution Testing

Conducting frequent and regular nutrient solution analyses lets producers detect trends in nutrient levels before problems arise. For soilless culture (stone wool, coco coir, etc.), analyze the following every 7–14 days to make sure the correct fertilizer is applied and to determine what adjustments are needed to compensate for plant consumption and weather conditions:

- feed solution (solution applied to the crop)
- rootzone solution (solution extracted from the bag)
- leachate (captured solution leaching from the bag)

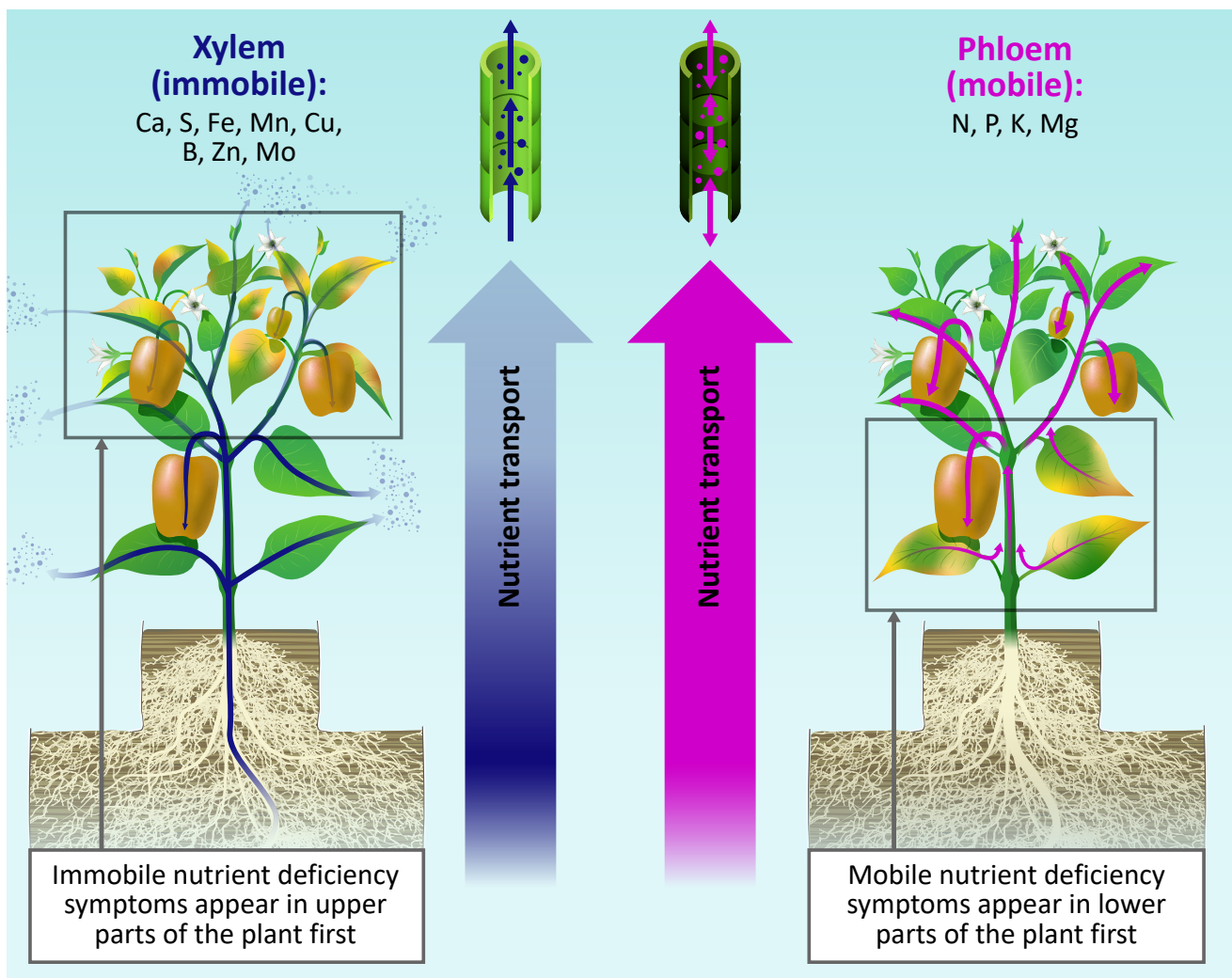


Figure 42. Immobile nutrients (left) vs. mobile nutrients (right).

This becomes more crucial when nutrient solutions are recycled. It is also important to monitor changes in ions such as sodium and chloride that are not necessary for plant growth, since these elements tend to accumulate in the nutrient solution, slowing plant growth.

Weekly analysis of nutrient film technique (NFT) solution from the reservoir provides similar information. Each test should include analysis of pH, EC, macronutrients and micronutrients (Table 21).

Besides nutrient analysis, it is also recommended that water be tested for microbes as discussed in more detail in [Chapter 7, Multi-Stage Filtration and](#)

[Disinfection](#) and dissolved oxygen levels as discussed in [Chapter 8, Growing Media](#).

Tissue/Foliar Testing

Plant tests provide information regarding the nutrient status of the crop, although adequate leaf nutrient content does not necessarily indicate the plant is not limited by nutrient supply. Regular testing reveals trends that allow producers to implement corrective measures before problems arise. At least once a month, conduct a foliar analysis.

Each crop has a specific leaf used for analysis:

- tomatoes — the 5th leaf from the growing tip on the main stem

- cucumbers — the 3rd leaf from the growing tip or from a lateral near the upper part of the crop canopy once topping has occurred (the leaf should be approximately 10 cm across to provide enough material for testing)
- peppers — a young, fully expanded leaf about 15 cm from the growing tip
- eggplants — a young, fully mature leaf about 15 cm from the growing tip
- lettuce — a mature leaf
- strawberry — a young, mature leaf from the middle of the crown

It is important to note that if the leaves were sprayed, especially with nutrient solution, they need to be rinsed with de-ionised or distilled water before being sent to a lab for analysis.

Wrap leaf samples from several different plants in a paper towel, place them in a clean plastic bag, seal the bag and place it in a standard brown envelope. Mail the sample or ship it by courier to the lab. Results from most labs will include the acceptable range

for nutrients for different crops and the results can also be compared to the values in [Table 22](#).

Soil Testing

In soil-grown greenhouse vegetable crops, conduct soil testing prior to planting to determine both the pre-plant and post-plant fertility program. Regular soil and tissue testing during the season is essential to ensure crops have received enough fertilizer ([Table 21](#)).

During the growing season, a regular soil analysis every 2 weeks helps maintain the ideal fertility program. Soil samples should represent the soil type in the greenhouse. Using a soil probe, take samples from several locations in the greenhouse to a depth of 20 cm. Mix these samples together and forward this mixture to the lab for analysis. Keep samples separate if there are different soil types or if a specific problem area exists. This allows for specific fertilizer programs for these locations.

Table 21. Guidelines for Greenhouse Growing Media Analyzed by the Saturated Media Extract (SME) Method¹

Legend: n/a = Not Applicable

Analysis	Low	Acceptable	Optimum	High	Very High
Soluble salt (EC, mS/cm)	0–0.75	0.75–2.0	2.0–3.5	3.5–5.0	5.0+
Nitrate-N (ppm)	0–39	40–99	100–199	200–299	300+
Phosphorus (ppm)	0–2	3–5	6–10	11–18	19+
Potassium (ppm)	0–59	60–149	150–249	250–349	350+
Calcium (ppm)	0–79	80–199	200+	n/a	n/a
Magnesium (ppm)	0–29	30–69	70+	n/a	n/a

¹ This technique involves creating a paste with a soil sample and distilled water. The filtrate is then analyzed for nutrients.

Source: The information in this table is historical data developed over time by Agriculture and Agri-Food Canada (AAFC) and Ontario Ministry of Agriculture, Food and Agribusiness (OMAFRA) staff at the Harrow Research and Development Centre, and by OMAFRA staff in Vineland.

Table 22. Guide to Nutrient Content of Leaf Tissue for Greenhouse Vegetables and Fruits

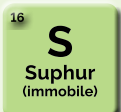
Legend: n/a = Not Applicable

Element	Tomatoes	Cucumbers	Peppers	Eggplant	Lettuce	Strawberry ¹
Macronutrients (%)						
Nitrogen	4.0–5.5	4.0–6.0	3.5–5.5	4.0–5.0	4.0–5.0	1.9–2.8 ¹
Phosphorus	0.3–0.65	0.6–1.0	0.4	0.3–0.6	0.6–0.8	0.25–0.4
Potassium	3.5–5.0	3.5–4.0	5.0–5.9	3.50–5.0	7.8–13.6	1.6–2.5
Calcium	1.6–3.2	2.4–3.2	2.8–3.2	1.0–2.50	0.8–1.2	0.7–1.7
Magnesium	0.36–0.5	0.36–0.5	0.5–0.75	0.3–1.0	0.25–0.5	0.3–0.49
Sulphur	1.3	0.3	0.5	n/a	0.3	0.4–0.6
Micronutrients (ppm)						
Manganese	55–165	55–165	55	40–250	55–110	50–200
Copper	5–10	7–12	5–10	n/a	6–15	7–19
Zinc	30–50	40–60	30–60	n/a	30–40	20–49
Boron	55–75	55–75	55–75	25–75	40–50	30–64
Iron	85–110	85–110	112	50–300	85–110	60–250

¹ <https://www.haifa-group.com/crop-guide/vegetables/strawberry-fertilizer/crop-guide-strawberry-1>

Source: The information in this table is historical data developed over time by Agriculture and Agri-Food Canada (AAFC) and Ontario Ministry of Agriculture, Food and Agribusiness (OMAFRA) staff at the Harrow Research and Development Centre, and by OMAFA staff in Vineland.

Table 23. Nutrient Function, Mobility and Symptoms of Deficiency and Toxicity

Nutrient (mobility)	Function	Deficiency Symptom	Toxicity Symptom
Macronutrients			
	Plant vigor and formation of amino acids.	• Light green lower foliage or whole plant in more severe cases. • Pale yellow flowers with thin heads, low vigor and hard, spindly plants with small fruit.	• Vegetative growth, strong thick stems, curled leaves and big flower trusses. • Poor flower development and fruit set with poor fruit quality. • Dark pitted lesions on stems if severe. • Reduced K uptake.
	Growth, fruit set and energy production.	• Purple underside of leaves, leaf veins and stem. • Bluish green colour of upper side of leaf. • Thin growth and poor cluster development, stunting, poor root colour, small curled leaves and poor flower development.	• Uncommon.
	Fruit quality, flavour and colour. N:K ratio is important (higher ratio leads to slower growth).	• Yellow margins of leaves. • Leaves scorched at ends, and some interveinal chlorosis. • Stunted and hard plants, blotchy ripening, boxy fruit and green shoulder. • Reduced fruit set and fruit weight.	• Reduced N and Mg uptake.
	Fruit quality, chlorophyll and photosynthesis.	• Interveinal yellowing and chlorosis of older leaves. • Purple underside of leaves if severe and poor fruit quality. • Related to high K.	• Uncommon.
	Cell wall and membrane integrity, cell elongation and division and fruit quality.	• No turgor, spots on upper stem, dark upper leaves followed by yellowing edges and poor roots. • Blossom end rot on fruit and dieback on growing tips.	• Goldspot/Goldspeck.
	Component of amino acids.	• Uncommon. • Stunting, reduced fruit production and pale yellow leaves.	• High salts. • Reduced uptake of Mo.

 Mobile
  Immobile
continued »

Table 23. Nutrient Function, Mobility and Symptoms of Deficiency and Toxicity (*continued*)

Nutrient (mobility)	Function	Deficiency Symptom	Toxicity Symptom
Micronutrients			
 Fe Iron (immobile)	Chlorophyll and photosynthesis.	- Chlorosis in young upper leaves and stem and appearance of brown spots. - Stunting	Uncommon.
 Mn Manganese (immobile)	Enzyme reactions and photosynthesis.	- Interveinal chlorosis and light-green veins. Becomes more yellow and brown spots appear at base of leaflets. - Mainly younger upper leaves. - Similar to Fe deficiency but veins remain green and symptoms may progress down plant.	Reduced Fe uptake.
 Cu Copper (immobile)	Enzyme reactions and photosynthesis.	- Dark-green younger leaves that frequently wilt. - Restricted plant growth. - Thinner stems and leaves, curled leaves and eventual chlorosis and necrosis. - Delayed flowering and poor roots.	- Burning root tips. - Chlorosis on young leaves, similar to Fe deficiency.
 B Boron (immobile)	Meristem development, cell wall development, fruit pollination and sugar transport.	- Brittle leaves, premature wilting and dieback of growing tips. - Yellow or orange-brown colour along margins of upper leaves, fruit fail and fruit drop. - Corky area around calyx.	Chlorosis.
 Zn Zinc (immobile)	Enzyme reactions.	- Uncommon. - Interveinal chlorosis and necrosis of older lower leaves. - Elongation of leaves, stunted growth and reduced fruit production.	Uncommon.
 Mo Molybdenum (immobile)	Enzyme reactions.	- Chlorosis, margins roll, stunting and small pale yellow or white interveinal area that spreads inward across the surface of the young leaves. - Lower leaves may wilt and role prematurely.	Uncommon.

 Mobile
  Immobile

[<< previous](#)

Glossary

Air exchange per hour — number of times a greenhouse changes all of its air with outside air in one hour.

Chelates — chemicals that interact with metal ions such as iron to allow them to dissolve in water and be available for uptake by plants.

Daily Light Integral (DLI) — calculation result for when you multiply the light intensity (in moles/m²/hour) by the photoperiod (in hours). This is the total accumulated amount of light that plants are receiving in one day measured in moles (mol/m²/day).

Dose — amount of a treatment and the length of time for that treatment (quantity and duration).

Electrical conductivity (EC) — measure of water salinity and total dissolved salts or total ions present in a solution in milliSiemens per centimetre (mS/cm).

Generative plants — plants that produce smaller leaves, thin stems and smaller, more numerous smaller flowers that are prominently displayed.

Fertigation — application of fertilizer and water through an irrigation system.

Half-life — the length of time a chemical reaction takes to convert 50% of a product.

Hyperfilter — filters typically used in reverse osmosis with pore size of 0.0001 µm.

Immobile nutrients — nutrients which move passively with water in the xylem by the pull of respiration.

Light Distribution — lighting options which include; top lighting (above the canopy), inter-lighting (within the canopy) or a combination of both. HPS and LED lights can be used in different ways.

Light Intensity — also referred to as photosynthetic photon flux density (PPFD), it measures the amount of PAR light that plants are receiving in micromoles (µmol) per metre squared (m²) per second.

Light Spectrum — light quality or light colour produced by the light fixtures measured in nanometres (nm). Broad spectrum white light typically covers the PAR spectrum (400–700 nm), blue light is 400–500 nm, green/yellow/amber light is 500–600 nm, red light is 600–700 nm and far-red light is 700–800 nm.

Microfilters — filters that have a pore size of 50 µm.

Mobile nutrients — nutrients that actively move through the plant with sugars in the phloem.

Nutrient film technique (NFT) — a hydroponic system where a shallow stream of fertigation runs down a slope while making contact with the roots of plants to allow uptake of nutrients.

Nanofilters — filters with pore size of 0.01 µm.

Photons — light particles that travel in a wave-like fashion.

Photoperiod — length of time there is light whether it is sunlight or artificial light, and it is typically measured in hours. When you multiply the light intensity (in mol/m²/hour) by the photoperiod (in hours) you get the daily light integral (DLI). This is the total accumulated amount of light that plants are receiving in one day (in mol/m²/day).

Photosynthesis — process whereby plants use certain wavelengths of sunlight to convert CO₂ and water into sugars (carbohydrates) and oxygen.

Photosynthetic acclimation — where the rate of photosynthesis drops and the benefits of elevated levels of CO₂ are not as pronounced as they were when the plants were first exposed to them.

Photosynthetic photon flux density (PPFD) — intensity of photosynthetically active radiation (PAR) and measured in $\mu\text{mol}/\text{m}^2/\text{second}$.

Photosynthetically active radiation (PAR) — the light between 400–700 nm in wavelength that is used for photosynthesis. Extended PAR (ePAR) includes far-red light (> 700 nm).

Relative humidity (RH) — ratio of the actual amount of water vapour present in a given amount of air (the absolute humidity) to the maximum amount of water vapour that can be held within that volume of air at a given temperature.

Respiration — process whereby carbohydrates produced by photosynthesis are broken down in the presence of oxygen to produce energy (i.e., adenosine triphosphate (ATP)).

Rootzone — environment where roots reside in a soilless cultivation system.

Saturation point — when a substance holds the maximum amount of water.

Tilth — physical state of soil when rocks and other debris have been removed.

Transpiration — movement of water vapour from the leaf into the atmosphere that occurs through open stomata.

Ultrafilters — filters with pore size of 0.02 μm .

Vapour pressure (VP) — result of water vapour exerting pressure in the air or within the leaf. It is directly related to temperature and RH. As temperature and RH increase so does VP.

Vapour pressure deficit (VPD) — difference between the vapour pressure inside and the air outside of the leaf. The greater the VPD, the greater the rate of transpiration and water loss.

Vegetative plants — plants that produce more large, thick, dark-green leaves than flowers and fruit, and less large, rough flowers.

Wavelength — length of wave the light photon travels, which can be measured in nanometres (nm). Each wavelength is associated with a different energy and colour of light.

Appendix A. Ministry Resources

Agricultural Information Contact Centre

Provides province-wide, technical and business information to commercial farms and agri-businesses.

Tel: 1-877-424-1300

E-mail: ag.info.omafra@ontario.ca

ONGreenhouseVegetables

For the latest information on:

- Commercial controlled environment agriculture including greenhouse fruits, vegetables and vertical farming
- Timely updates and technical information on production and integrated pest management
- GrowON educational series workshops/webinars
- Greenhouse Vegetable Course

Visit the Blog at

ONGreenhouseVegetables.ca

Ontario Crop Protection Hub

Use this tool on any device to find:

- Proper rates and application protocols for legally registered insecticides, fungicides and herbicides
- Up-to-date information on product efficacy against pests
- Strategies to support environmental stewardship
- Information to help growers manage pesticide resistance

Visit the Ontario Crop Protection Hub at

Ontario.ca/cropprotection

CropIPM

IPM info at your fingertips. The new CropIPM tool includes:

- Up-to-date IPM information for key Ontario pests
- A new 'Identify' feature to help you identify pests and disorders
- An expanded offering of crop specific information
- Scouting calendars
- Comparisons of often-confused-with pests
- Details on soil diagnostics and herbicide injury

Visit the Crop IPM Tool at
[Ontario.ca/cropIPM](https://ontario.ca/cropIPM)



Appendix B. Other Resources

Agriculture & Agri-Food Canada (AAFC)

Agriculture and Agri-Food Canada supports the Canadian agriculture and agri-food sector through initiatives that promote innovation and competitiveness.

<https://agriculture.canada.ca/en>

AAFC Research Centres

www.agriculture.canada.ca/en/agricultural-science-and-innovation/agriculture-and-agri-food-research-centres-and-collections

Canadian Food Inspection Agency — Plant Protection

Services and information on plant pests and invasive species, import, export, trade, fertilizers, soil and soil-related matter, grains and field crops, seeds, cannabis, forestry, horticulture. <https://inspection.canada.ca/en/plant-health>

Canadian Greenhouse Conference

The Canadian Greenhouse Conference is a not-for-profit corporation and Canada's

foremost event and connection point for commercial growers of crops produced in a controlled environment.

<https://www.canadiangreenhouseconference.com/>

Greenhouse Canada

National business magazine published exclusively for commercial greenhouse growers in Canada.

<https://www.greenhousecanada.com/>

University of Guelph — Plant Agriculture

Canada's largest and most diverse applied plant biology department. A research intensive department within the Ontario Agricultural College dedicated to teaching, research and service related to horticultural crops, turfgrass, landscape species and field crops. www.plant.uoguelph.ca

Lab Services Division

www.uoguelph.ca/labserv/

Appendix C. Metric System and Abbreviations

Metric units
Linear measures (length)
10 millimetres (mm) = 1 centimetre (cm)
100 centimetres (cm) = 1 metre (m)
1,000 metres = 1 kilometre (km)
Square measures (area)
100 m × 100 m = 10,000 m ² = 1 hectare (ha)
100 ha = 1 square kilometre (km ²)
Cubic measures (volume)
Dry measure
1,000 cubic millimetres (mm ³) = 1 cubic centimetre (cm ³)
1,000,000 cm ³ = 1 cubic metre (m ³)
Liquid measure
1,000 millilitres (mL) = 1 litre (L)
100 L = 1 hectolitre (hL)
Weight-volume equivalents (for water)
(1.00 kg) 1,000 grams = 1 litre (1.00 L)
(0.50 kg) 500 g = 500 mL (0.50 L)
(0.10 kg) 100 g = 100 mL (0.10 L)
(0.01 kg) 10 g = 10 mL (0.01 L)
(0.001 kg) 1 g = 1 mL (0.001 L)
Weight measures
1,000 milligrams (mg) = 1 gram (g)
1,000 g = 1 kilogram (kg)
1,000 kg = 1 tonne (t)
1 mg/kg = 1 part per million (ppm)
Dry-liquid equivalents
1 cm ³ = 1 mL
1 m ³ = 1,000 L
Metric conversions
5 mL = 1 tsp
15 mL = 1 tbsp
28.5 mL = 1 imp. fl. oz.

Handy metric conversion factor (approximate)
litres per hectare × 0.4 = litres per acre
kilograms per hectare × 0.4 = kilograms per acre

Application rate conversions
Metric to imperial or U.S. (approximate)
litres per hectare × 0.09 = Imp. gallons per acre
litres per hectare × 0.11 = U.S. gallons per acre
litres per hectare × 0.36 = Imp. quarts per acre
litres per hectare × 0.43 = U.S. quarts per acre
litres per hectare × 0.71 = Imp. pints per acre
litres per hectare × 0.86 = U.S. pints per acre
millilitres per hectare × 0.014 = U.S. fluid ounces per acre
grams per hectare × 0.014 = ounces per acre
kilograms per hectare × 0.89 = pounds per acre
tonnes per hectare × 0.45 = tons per acre

Imperial or U.S. to metric (approximate)
Imp. gallons per acre × 11.23 = litres per hectare (L/ha)
U.S. gallons per acre × 9.35 = litres per hectare (L/ha)
Imp. quarts per acre × 2.8 = litres per hectare (L/ha)
U.S. quarts per acre × 2.34 = litres per hectare (L/ha)
Imp. pints per acre × 1.4 = litres per hectare (L/ha)
U.S. pints per acre × 1.17 = litres per hectare (L/ha)
Imp. fluid ounces per acre × 70 = millilitres per hectare (mL/ha)
U.S. fluid ounces per acre × 73 = millilitres per hectare (mL/ha)
tons per acre × 2.24 = tonnes per hectare (t/ha)
pounds per acre × 1.12 = kilograms per hectare (kg/ha)
pounds per acre × 0.45 = kilograms per acre (kg/acre)
ounces per acre × 70 = grams per hectare (g/ha)

Dry weight conversions (approximate)	
Metric	Imperial
grams or kilograms/hectare	ounces or pounds/acre
100 g/ha	= 1½ oz/acre
200 g/ha	= 3 oz/acre
300 g/ha	= 4¼ oz/acre
500 g/ha	= 7 oz/acre
700 g/ha	= 10 oz/acre
1.10 kg/ha	= 1 lb/acre
1.50 kg/ha	= 1¼ lb/acre
2.00 kg/ha	= 1¾ lb/acre
2.50 kg/ha	= 2¼ lb/acre
3.25 kg/ha	= 3 lb/acre
4.00 kg/ha	= 3½ lb/acre
5.00 kg/ha	= 4½ lb/acre
6.00 kg/ha	= 5¼ lb/acre
7.50 kg/ha	= 6¾ lb/acre
9.00 kg/ha	= 8 lb/acre
11.00 kg/ha	= 10 lb/acre
13.00 kg/ha	= 11½ lb/acre
15.00 kg/ha	= 13½ lb/acre

Conversion tables – metric to imperial (approximate)
Length
1 millimetre (mm) = 0.04 inches
1 centimetre (cm) = 0.40 inches
1 metre (m) = 39.40 inches
1 metre (m) = 3.28 feet
1 metre (m) = 1.09 yards
1 kilometre (km) = 0.62 miles
Area
1 square centimetre (cm ²) = 0.16 square inches
1 square metre (m ²) = 10.77 square feet
1 square metre (m ²) = 1.20 square yards
1 square kilometre (km ²) = 0.39 square miles
1 hectare (ha) = 107,636 square feet
1 hectare (ha) = 2.5 acres

Volume (dry)

1 cubic centimetre (cm ³)	= 0.061 cubic inches
1 cubic metre (m ³)	= 1.31 cubic yards
1 cubic metre (m ³)	= 35.31 cubic feet
1,000 cubic metres (m ³)	= 0.81 acre-feet
1 hectolitre (hL)	= 2.8 bushels

Volume (liquid)

1 millilitre (mL)	= 0.035 fluid ounces (Imp.)
1 litre (L)	= 1.76 pints (Imp.)
1 litre (L)	= 0.88 quarts (Imp.)
1 litre (L)	= 0.22 gallons (Imp.)
1 litre (L)	= 0.26 gallons (U.S.)

Weight

1 gram (g)	= 0.035 ounces
1 kilogram (kg)	= 2.21 pounds
1 tonne (t)	= 110 short tons
1 tonne (t)	= 2,205 pounds

Pressure

1 kilopascal (kPa)	= 0.15 pounds/in. ²
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Speed

1 metre per second	= 3.28 feet per second
1 metre per second	= 2.24 miles per hour
1 kilometre per hour	= 0.62 miles per hour

Temperature

$$^{\circ}\text{F} = (^{\circ}\text{C} \times 1.8) + 32$$

Conversion tables – imperial to metric (approximate)

Length

1 inch	= 2.54 cm
1 foot	= 0.30 m
1 yard	= 0.91 m
1 mile	= 1.61 km

Area

1 square foot	= 0.09 m ²
1 square yard	= 0.84 m ²
1 acre	= 0.40 ha

Volume (dry)

1 cubic yard	= 0.76 m ³
1 bushel	= 36.37 L

Volume (liquid)

1 fluid ounce (imp.)	= 28.41 mL
1 pint (imp.)	= 0.57 L
1 gallon (imp.)	= 4.55 L
1 gallon (U.S.)	= 3.79 L

Weight

1 ounce	= 28.35 g
1 pound	= 453.6 g
1 ton	= 0.91 tonne

Pressure

1 pound per square inch	= 6.90 kPa
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Temperature

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) \times .5556$$

Abbreviations

%	= per cent
cm	= centimetre
cm ²	= square centimetre
EC	= electrical conductivity
e.g.	= for example
g	= gram
hr	= hour
ha	= hectare
HP	= horsepower
J	= joule
kg	= kilogram
km/h	= kilometres per hour
kPa	= kilopascal
L	= litre
m	= metre
m ²	= square metre
mJ	= millijoule
mL	= millilitre
mol	= mole
mm	= millimetre
mS	= milliSiemes
m/s	= metres per second
nm	= nanometres
ppm	= parts per million
s or sec	= second
t	= tonne
μ	= micro
μm	= micrometres
μmol	= micromole
W	= Watts



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