THIRD EDITION

Greenhouse Management

A Guide to Operations and Technology

Ted Goldammer

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Feedback/Acknowledgement

In preparing such a book we anticipate there will be errors, and we encourage the reader to send us comments. From simple typographical errors, to missing topics, errors in data or interpretation, and even suggestions for new approaches to explaining greenhouse management, all suggestions are encouraged. Please send your ideas to: apexbookpub@gmail.com. In closing, we acknowledge the work of the many researchers in the international horticulture community that we have drawn upon in formulating this book, and also appreciate the feedback from greenhouse managers who helped shape the book.

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Preface to Third Edition

Greenhouse Management: A Guide to Operations and Technology is a complete reference book on greenhouse technologies and operations, and the science of growing crops. Written in laymen's terms, the book systematically starts the reader off by providing an in-depth discussion on greenhouse structures, design, and glazing; heating, cooling, and environmental control systems; growing media; temperature and lighting; carbon dioxide enrichment; plant nutrition, irrigation, and fertigation; seed/plant propagation; chemical growth regulation; and pest management. Finally, a series of appendices provide numerous data relevant to greenhouse management and operations. The information in this book is distilled from a variety of sources, including scientific literature, extension publications, trade publications, reader feedback, and industry experts, who have generously shared their years of experience. This book also has the added value of numerous citations to more in-depth discussion on many topics. The book is thoughtfully organized in an easy-to-read format presenting a seamless flow of topics within chapters. *Greenhouse Management* has removed some of the intuition and guesswork in understanding greenhouse operations. The result is a more consistent product of higher quality providing a practical "real world" application of greenhouse operations. The primary audience includes growers, technical industry representatives, and university horticulture students.

New and Key Features of the Third Edition:

- New chapters on greenhouse curtains and artificial intelligence in greenhouses
- A better introduction to greenhouse lighting
- Updated information on growing media
- Expanded coverage on irrigating greenhouse crops and micro-irrigation systems
- A dedicated chapter on greenhouse water treatment and filtration
- Revised and expanded information on fertigation
- Expanded coverage on plant nutrition of greenhouse crops
- Revised and expanded information on pesticide application and equipment
- A number of important appendices have also been added

1 Greenhouse Structures and Design

Greenhouses are used to provide optimal environments for plant growth and development. The greenhouse design must deal with the local outdoor circumstances, like minimum, maximum, and average temperature, humidity, solar radiation, clearness of the sky, precipitation (e.g., rain, hail, and snow), and wind. Some of the considerations of a greenhouse design are location, orientation, site selection, drainage, structure, foundation, flooring, glazing, and ventilation facilities, together with the equipment needed to control the climate inside the greenhouse. The location and orientation of a greenhouse determine the amount of light that enters it. Determining the best location to erect the greenhouse is an important decision. A suitable greenhouse location is where the sun hits the greenhouse all day, and no shadows are cast. Greenhouses can be classified as freestanding or gutter-connected. A freestanding greenhouse can have a Quonset (i.e., hoop), Gothic, or gable roof shape. A gutter-connected greenhouse is a series of bays with gable or Quonset arches connected at the gutter level. Structural members used for the greenhouse *skeleton*, must be strong enough to prevent structural failure during adverse weather conditions but should be kept to a minimum size and number to reduce the amount of shading and to provide for maximum light transmission. Structure framing materials are made of aluminum, galvanized steel, polyvinyl chloride (PVC) pipe, or such woods as redwood, cedar, or cypress. A greenhouse has a large expanse of glazing on its sides and roof so that the plants are exposed to natural light for much of the day. Glass has been the traditional glazing material. Still, plastic films, such as polyethylene or polyvinyl, and fiberglass or polycarbonate are increasingly used.

1.1 Greenhouse Site Selection

Careful planning before construction is essential in developing a successful, profitable greenhouse production system. Before starting, it is important to have an idea of the type of plants you want to raise and sell and a decision as to whether you wish to be retail or wholesale. Sometimes, one or two factors are so important that the choice of site is obvious, but more commonly, each site has good and bad attributes. If desired, make a list of potential greenhouse sites and compare them using a decision matrix. The following major factors should be investigated before greenhouse plans go beyond paper.

Microclimate

The primary limiting factor to greenhouse crop production is low light intensity during the winter. Areas with frequent fog, inclement weather, or shadows cast by trees or tall mountains are poor for greenhouse crops. Other environmental considerations include: large bodies of water will heat up and cool down much slower than land masses; high wind that can cause structural damage and suck heat away from the greenhouse; blowing dust and sand which can braze the greenhouse glazing; and lastly, snow. The local topography must be suitable for effective drainage of cold air during calm nights. Areas that are well-illuminated and free from shadows (e.g., hills, buildings) are preferred.

Water Availability and Quality

One of the most frequently overlooked requirements in the establishment of a greenhouse is the quantity and quality of the water. A sufficient quantity of high-quality water is extremely important to produce greenhouse crops. The need for frequent irrigation requires careful planning and management to ensure that operations have sufficient water to maintain adequate supplies for crop production. Although water is usually obtained from deep wells or ponds, generally municipal systems can also supply water for greenhouse production. However, the economic costs should be considered before becoming totally dependent on city water. Equally important to quantity is the quality

Life Span of Plastic Film

The greenhouse cover is likely to last longer in mild climates than in climates with extreme cold, heat, rain, snow, or hail. Heavy precipitation is more likely to weigh your greenhouse cover down, causing it to stretch. Extreme changes in temperature can cause your plastic to shrink and grow. Climates with heavy dirt and dust can cause your greenhouse to accumulate dirt, and areas with heavy trees or jutting branches pose a risk to your greenhouse. At the same time, high winds can cause scratches from blowing debris. Understanding how your greenhouse frame materials will interact with the greenhouse plastic sheeting can help you extend the life of your cover. For example, PVC or polyester frames can react chemically with polyethylene sheeting, resulting in weak spots where the materials touch, which will cause the greenhouse plastic to deteriorate in those areas. Wooden frames can splinter, leading to a higher possibility of holes and tears. Metal frames conduct heat and cold, making the plastic sheeting brittle or causing it to melt into the greenhouse frame. Material thickness and UV resistance are a couple of the factors that play an important role in the life of the sheeting. The thicker the sheeting, the less susceptible to tears and rips it will be. UV inhibitors extend the life of greenhouse plastic sheeting so it can last season after season underneath the scorching hot sun. Greenhouse felt tape creates a cushion between the frame of the greenhouse and the greenhouse cover, preventing the chances of premature deterioration, snags, and tears. Felt tape prevents the greenhouse cover from over-exposure to hot metal frames, protects your greenhouse cover from direct chemical reactions, reduces friction against rough edges and splinters, and allows for easy movement. Reinforced greenhouse repair tape is a fast way to patch minor snags or rips. Repairing greenhouse covers is an inexpensive and time-effective way to extend the life of your greenhouse cover. Latex paint is another solution for PVC frames. The paint creates a barrier between the greenhouse cover and the frame to prevent the chemical reaction that happens when they are in contact with each other under the hot sun.

Poly-Locking System

The poly-locking system for the greenhouse is a component that must be thoroughly researched before installation (Figure 2.3). Poly films are fastened to the house at the edges by special poly-locking extrusions. Many brands of extrusions for locking plastic films are available. Most rely on friction via a clamping mechanism to hold the edges of the poly in place. The most durable extrusions are those made of aluminum. The main difference among extrusions for plastic film locking is in the specific details regarding the clasping mechanism and how fast the poly can be released from the extrusion when the poly film is replaced. Some of the plastic film-locking extrusions rely on an aluminum channel into which the double-layered poly is locked by a tight-fitting strip or wedge. Some of these are designed so that the fit of the wedge strip becomes tighter in reaction to the natural pull of the polyethylene sheets.

Figure 2.3 Poly locking system

2.2 Rigid Plastics

Rigid plastic coverings include fiberglass-reinforced plastic (FRP) rigid panels, polycarbonates, and acrylics. Light transmission through rigid plastics is very good, although it usually decreases over time as the plastics age and turn yellow due to the amount of UV radiation contained in sunlight. The large sheets are much lighter than glass and require fewer support bars to attach them to the greenhouse frame. However, these rigid panels are not so easy to install on curved roofs.

Fiberglass Rigid Plastic Panels

Fiberglass-reinforced plastic (FRP) rigid panels have been used in greenhouse coverings since the 1950s, but their popularity has declined in recent years. Fiberglass is available in flat and corrugated configurations (Figure 2.4). Corrugated panels are commonly used for greenhouse roofs, as their corrugated shape lends strength and rigidity to the panels. Flat panels are usually used for sidewalls, windows, and vents. Although FRP panels are classified as rigid plastic, they are flexible enough to be bent in a curve to fit the framework of a Quonset-type or arch-type greenhouse.

curtain system, the curtain panels are pulled flat across the width of the greenhouse at gutter height. Though the volume of greenhouse space that is heated is minimized in this configuration, the amount of cold air above the system is maximized. This makes it harder to mix and reheat the air above the system when it uncovers in the morning. These systems require less installation labor than a typical truss-to-truss system, but gutter systems are not ideal for every greenhouse.

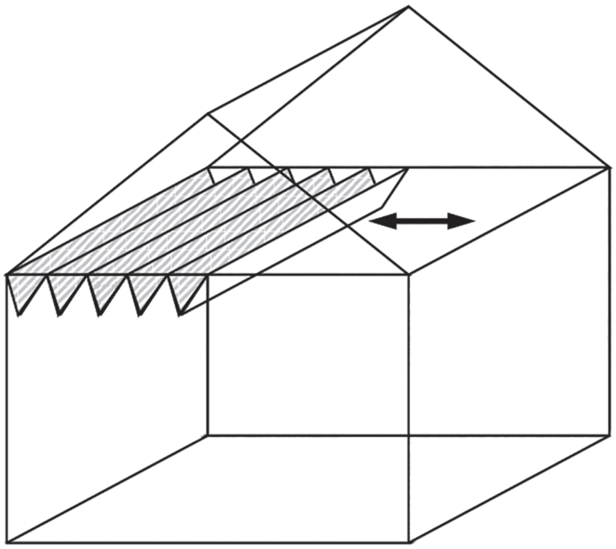

Figure 3.2 Gutter-to-gutter curtain layout

If unit heaters or circulation fans are mounted above the gutter level, the curtain will block them from circulating the air under the system where the crop is grown. In many gutter-connected greenhouses, a lightweight truss can be installed below the screen (energy truss) to support heating, horizontal air flow fans, water, electrical systems, and hanging baskets. When covered for shade/cooling, the space above a gutter-to-gutter system becomes very hot, and this trapped hot air reduces the cooling effect of the shade. The attic space above the curtain can be ventilated with a louver and exhaust fan at opposite gable ends of each greenhouse to reduce this effect. Because the curtain panels are as wide as the greenhouse, when the curtain is retracted, the curtain material forms a large bundle under each gutter. This bundle can be a source of unwanted shade.

Truss-to-Truss Curtain System

The truss-to-truss type has a curtain section between each truss, so, for example, a 100-foot (30m) long greenhouse with 10-foot truss spacing could have 10 curtain sections on (Figure 3.3). When the curtain is opened or closed, each section moves at the same time and the same amount, covering the area between trusses. Three types of configurations are used for truss-to-truss curtain systems: flat at gutter height, slope-flat-slope, and slope-slope.

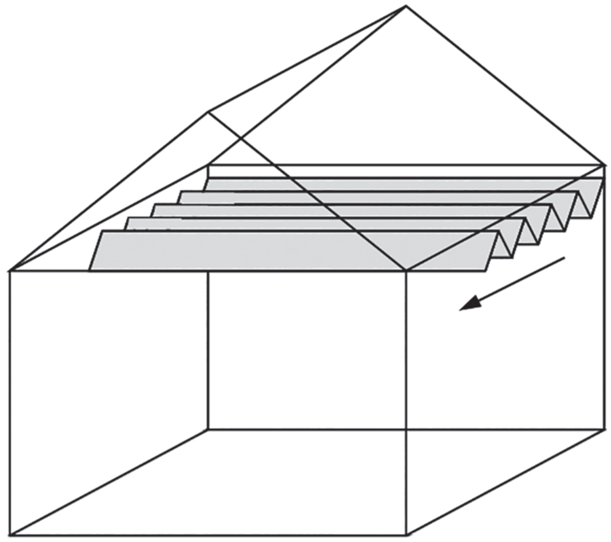

Figure 3.3 Truss-to-truss curtain layout

Flat at Gutter Height

Flat, at-gutter height systems draw shade curtains from truss to truss at the height of the gutter. As with the gutter-to-gutter system, this configuration minimizes the volume of greenhouse space to be heated and is relatively easy to install. It has the same restrictions on equipment in the gables and prevents the grower from suspending hanging baskets from the bottom chord of the truss. Adopting this system may require moving equipment—lights, irrigation tubing, hanging basket holders, heaters, heating pipes, and other equipment can increase the cost of using gutters or trusses.

Slope-Flat-Slope

Slope-flat-slope, where the profile of the curtain system follows each slope of the roof part way up the truss, with a flat section at the top of the greenhouse joining the two sloped segments (Figure 3.4). This slope-flat-slope is used in greenhouses with wider spans to allow space underneath the screen installation for other greenhouse equipment such as lamps, horizontal air flow (HAF) systems, watering booms, and basket hanging systems. The bottom chords of the trusses remain available for hanging baskets. This configuration leaves clearance for roof vents and provides a chimney effect when used for shade/cooling if a 6-to-12-inch (15–30cm) gap is left instead of fully covering the system.

Slope-Slope

Slope-slope, where the profile of the system parallels a line drawn from the gutter to the peak of the truss (Figure cooling during the warmer parts of the growing season. For best results during summer months, windward wall vents should be located at approximately plant canopy level.

Determining Air Intake Vent Size

To provide adequate airflow and ventilation, the surface area of the vent openings should be at least 1.25 to 1.5 per 1,000 CFM (0.14 m^2 per 0.47 m^3/sec) or sized to provide an apparent velocity of 700 feet per minute (FPM). The cross-sectional area can be determined by dividing the air capacity of the fan in CFM by the inlet design velocity in FPM, which gives excellent mixing. Following is an example of a suggested procedure for determining the appropriate size of a ventilation inlet:

Using the example cited earlier, a 44.5 x120 foot greenhouse with three 14,200 CFM fans would require the following inlet area:

Area = CFM ÷ velocity

Without shade curtain:
Area = 42,720 ÷ 700 = 61 square feet
With shade curtain:
Area = 24,000 ÷ 700 = 35 square feet

For example, three 48 x 48-inch and one 40 x 40-inch openings with motorized shutters would provide a total of 61 square feet of ventilation opening. Ideally, the inlet should be controlled by a pressure sensor that opens and closes the inlet to maintain a steady pressure difference from outside the house to inside. This keeps the airflow patterns within the greenhouse steady and helps prevent dead air spaces.

Thermostat Selection and Placement

Exhaust fans and vent motors are usually controlled by thermostats or, preferably, by a computerized climate control system. The control range of a thermostat should be from 45 to 90 degrees F (7–32°C). A smaller control range is not recommended because the fans will cycle on and off more often than is necessary. Select accurate thermostats that will withstand the greenhouse environment and maintain their calibration. Usually these have a wide differential between the off and on position, sometimes as much as 6 to 8 degrees F (3.3–4.4°C). Using this type of thermostat can result in a high electric bill. For example, if the thermostat is set at the desired setpoint temperature of 75 degrees F (24°C), a +/- 2-degree thermostat will shut the fan off at 73 degrees F (23°C), whereas a +/- 5-degree thermostat will allow the fan to cool the greenhouse to 70 degrees F (21°C). Thermostats should be at plant height near the center of the greenhouse to ensure accurate readings of the temperature around the plants. Keep them away from exterior walls or from direct influence from the heater, and shield them from the sun. Even the best heating and ventilation system has little value if its thermostats do not work properly or if they are incorrectly located.

6.4 Fan and Pad Evaporative Cooling Systems

The most commonly used evaporative cooling system used in greenhouses is the fan and pad evaporative cooling system (Figure 6.10). With this type of system, exhaust fans are placed on one wall of the greenhouse, and pads are on the opposite wall. The fans exhaust air from the greenhouse and draw in fresh air through the pads. Water is continuously circulated over and through the pad cells during operation. As air flows past the moist pad surfaces, some of the moisture evaporates into the air stream. Heat is withdrawn from the air during this process, and the air leaves the pads at a lower temperature with higher moisture content. The drop-in temperature depends on how much water the air can absorb (a function of the relative humidity), how evenly the pad media is wetted, and how long the air is exposed to the pad (a factor of turbulence, wetness, and speed of air movement).

Figure 6.10 Evaporative cooling pad system

As the cooled air moves through the greenhouse toward the exhaust fans, it picks up heat from solar radiation, plants, and soil, and the temperature of the air gradually increases. Therefore, such systems experience a temperature gradient between the inlet (pad) and the outlet (exhaust fans) sides of the greenhouse. Evaporative cooling can be used to cool the greenhouse as much as 10 to 20 degrees in temperate regions. The transmissivity of some plastics decreases with age and exposure to sunlight, so replace them when they have reached their expected lifetime. If whitewash is applied, ensure it is completely removed each autumn. A common goal is to minimize overhead obstructions that would shade plants below. Therefore, consider the overhead footprint of all equipment, including that for heating, lighting, irrigation, and horizontal air flow. When growing hanging baskets above another crop, consider the effects of when they are hung, density, and basket color on light transmission to plants below. When possible, grow shade-tolerant crops under hanging baskets; in northern regions, delay hanging baskets above a crop until at least March and use white or other light-colored baskets.

Calculating Daily Light Integral

There are three ways to calculate the DLI in the greenhouse: (1) quantum sensors, (2) foot candle meter, and (3) DLI maps.

Quantum Sensors

A quantum light sensor will measure the light that is used for photosynthesis, or photosynthetically active radiation (PAR). Quantum sensors measure instantaneous light, reported in micromoles (μmol) per square meter (m^{-2}) per second (s^{-1}), or: $\mu mol \cdot m^{-}m^{-2} \cdot s^{-1}$ of PAR, which allows the summation into $mol \cdot m^{-2} \cdot d^{-1}$ or moles/day. From this information the grower can then calculate the DLI. Many greenhouse growers use automated systems with quantum sensors connected to a data logger (Figure 8.4). If connected to a computer control system such as those from Argus, Hoogendoorn, or other similar products, the grower can easily monitor and automatically calculate the DLI, making sure plants get the light they need. However, smaller-scale growers can make use of portable DLI quantum sensors, which can be moved around within the greenhouse to get an approximate reading for the DLI at the end of each 24-hour period.

Light can be quantified that reaches an area during a 24-hour period, referred to as the daily light integral (DLI). The unit for DLI is moles of PAR per square meter and day ($mol \cdot m^{-2} \cdot s^{-1}$) and is sometimes simplified to "moles/day"). The relationship between the average $\mu mol \cdot m^{-2} \cdot s^{-1}$ and $\mu mol \cdot m^{-2} \cdot d^{-1}$ can be calculated from the number of $\mu mol \cdot m^{-2} \cdot s^{-1}$ (average instantaneous light level) x 60 (seconds/minute) x 60 (minutes/hour) x the number of hours (e.g., x=24 hours per day if instantaneous light is averaged over a whole day and night) divided by 1,000,000 (micromoles/mole) = c $mol \cdot m^{-2} \cdot d^{-1}$ (or $mol \cdot m^{-2} \cdot d^{-1}$). For example, if the average light intensity during a 24-hour period was 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$, then 150 x 60 x 60 x 24/1,000,000 = 13.0 $\mu mol \cdot m^{-2} \cdot d^{-1}$ of accumulated light energy (DLI).

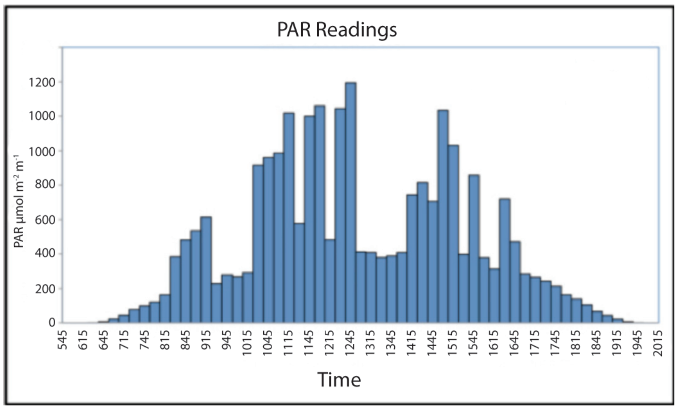

Figure 8.4 An example of PAR data recorded every 15 minutes throughout the day using a quantum sensor and data logger.

Table 8.2 shows an example of how daily light integral is calculated using a quantum sensor. In this example, light was measured once every hour. The calculated average of these 24 values was determined to be 201 $\mu mol \cdot m^{-2} \cdot d^{-1}$. To convert this average value into a DLI, it is multiplied by 0.0864, and the outcome is 17.3664, which can then be rounded to 17.4 $mol \cdot m^{-2} \cdot d^{-1}$ or moles/day. For accurate DLI calculations, it is important to measure PAR frequently, especially on cloudy days, when PAR can fluctuate rapidly, or in greenhouses, where the PAR sensor may at times be shaded by the greenhouse structure. In such cases, it is recommended to measure PAR once per minute or more often.

Table 8.2 Calculating Daily Light Integral

Light intensity values recorded once per hour from midnight to midnight ($\mu mol \cdot m^{-2} \cdot d^{-1}$)	Average light intensity ($\mu mol \cdot m^{-2} \cdot d^{-1}$)	Calculated DLI ($\mu mol \cdot m^{-2} \cdot d^{-1}$)
0, 0, 0, 0, 44, 102, 198, 255, 410, 454, 600, 532, 627, 466, 376, 303, 187, 91, 45, 47, 44, 43, 0, 0	201	17.37

Once the DLI for the greenhouse has been calculated, it is possible to compare this to the optimal level for the types of plants being grown and adjust light levels as required. For plants that have specific day-length requirements for flower initiation, it may not be possible to simply extend the number of hours the lights are run to increase the DLI

Figure 12.11 Rockwool block

Figure 12.12 Rockwool slab

12.3 Common Media Amendments

A variety of amendments may be added to growing media during the mixing process, including limestone, iron sulfate, wetting agents, fertilizers, and biological control agents for controlling diseases. If the decision is made to use amendments, uniform incorporation is important because plant roots have access to only a limited volume of growing media in the relatively small containers used in greenhouses. Uneven mixing of incorporated fertilizers is one of the major factors causing uneven growth in container greenhouse stock.

Limestone

In most cases, greenhouse growers need to be concerned about raising the substrate's pH since most of the organic substrates are acidic (e.g., sphagnum peat). The most commonly used material is either calcitic ($CaCO_3$) or dolomitic limestone (a mixture of $CaCO_3$ and $MgCO_3$). Generally, calcitic limestone is more reactive than dolomitic limestone. Thus, calcitic limestone will adjust (raise) substrate pH faster and may raise the substrate pH higher than the same amount of dolomitic limestone. Dolomitic limestone is preferred because it is a combination of calcium and magnesium carbonate. There are three types of liming materials. Pulverized lime is powdered lime; it has a quick effect but does not last long in the substrate. Pelletized lime is pulverized lime with a sticking agent that is dissolved with water. Its longevity is only slightly longer than pulverized lime alone. Granular lime has larger particles, so it lasts much longer than pulverized or pelletized lime. It is recommended that for crops that stay in the greenhouse for longer than 6 months, a mixture of pulverized and granular lime be incorporated.

Application Rates

The amount of lime required to adjust the pH will depend on the starting pH, the desired pH, the particle size of the limestone (i.e., small particles act faster than large ones), the type of substrate, and the alkalinity of irrigation water used. Agricultural and horticultural limestones are considered soft crystals that react quickly with acid. This is more desirable for adjusting media formulated with peat moss, pine bark, or coconut coir. Therefore, determining the rate of limestone to incorporate into a media to change its pH depends on the substrates used as well as the limestone's properties (e.g., type, particle size, and hardness). Because of all the factors that can affect the reaction of limestone when added to a substrate, it can be difficult to make specific recommendations regarding the amount of limestone to add to a substrate to achieve a specific pH. As a result, greenhouse managers should experiment to determine exactly how a given amount of lime or limestone will affect the pH of the intended substrates. The greatest increase in pH usually occurs within the first 2 days of mixing. However, the pH will continue to increase and will equilibrate after 7 to 14 days. Therefore, it is generally recommended that the pH of the substrate be tested after 7 days. When conducting tests, it is important that the substrate be moist in order for the limestone to react and increase the pH.

manufacturers have developed capillary mat systems that have a bottom layer of polyethylene film and an upper layer of film with many closely spaced micro-perforations that allow the plants to take up water from the mats, all integrated into one mat system that can be rolled out on the bench top. Commonly, the top plastic layer has various markings that make it easy to space the crop out evenly. These new mat systems help alleviate the disadvantage of staying wet, allow for easier cleaning between crops, and have a longer life expectancy than older mats.

Containers

With a capillary mat system, pots with flat bottoms are set onto a capillary mat. Containers must be saturated before being placed on capillary mat systems to ensure effective water uptake. The capillary mats must stay continuously saturated and in good contact with the bottoms of pots so that capillary action will draw water from the mats into the potting media. If the containers are disturbed in some way and the capillary action is destroyed, the pots must be re-watered from the top to reestablish the capillary action. The pots and media must be heavy enough to keep good contact with the capillary mat surface. Plastic pots are preferred to clay pots for use with the capillary system. The bottom of the plastic pot should have several holes to ensure good contact with the pad. Single-hole pots, pots with projecting feet, and pots that have holes on the sidewall are not recommended. Containers less than 8.5 inches (22cm) tall (#2 container) have been found suitable for irrigation with capillary mats, provided the media was fine enough to allow for the water to rise.

Ebb-and-Flow System

Ebb-and-flow benches (also called ebb-and-flood benches) combine an elevated benching system with a closed subirrigation system (Figure 15.7). It provides for individual watering and fertigation of a number of different plants on different spacing without individual feed lines going to each plant and without overhead watering. Commercial ebb-and-flow systems are used chiefly for plants that are on the production tables for a relatively short period of time, such as seedlings and the production of potted plants in the floriculture industry. As with other closed irrigation systems, the nutrient solution is recirculated, and EC, pH, and often temperature levels are adjusted at the main nutrient reservoir.

Advantages and Disadvantages

The ebb-and-flow system is one of the simplest hydroponic systems to set up and use, but it still takes some experience and effort to master. The ebb-and-flow system costs are usually very low in comparison to many other substrate systems because it doesn't require any high-tech, expensive components. The ebb-and-flow system is well-used because it can use many different types of growing media, such as expanded clay pellets, perlite, sphagnum moss, and rockwool.

The disadvantage of an ebb-and-flow system is the high relative humidity that can build up in the canopy of plants. This situation can lead to condensation and, ultimately, to foliar diseases. To combat this problem, growers frequently place heating beneath their benches, which helps to dry the air in the plant canopy and sets up air currents during the

Figure 15.7

An ebb-and-flow system, also known as a flood and drain system, relies on intermittent water delivery (flood) to a plant or series of plants held in an inert medium.

Lime Deposition Potential

Lime deposition potential (LDP) is an indicator used to evaluate whether lime deposition could happen through precipitation of calcium or magnesium carbonates (lime) out of the irrigation water, which leaves white residues or deposits. Factors affecting lime deposition are higher temperatures, higher pH, loss of carbon dioxide in the water, and evaporation. As water passes through the irrigation system, any of these environmental effects can cause deposition on the equipment, vegetation, and fruit. Lime will deposit in the irrigation distribution system, causing clogging of components, especially drip emitters. Drip or micro-irrigation systems are prone to problems from clogging. If fertigating with irrigation water of high lime concentrations, nutrients can precipitate within the system, not be available to the plants, and plug emitters. Irrigation water with high concentrations of lime can increase soil pH and reduce the solubility and availability of phosphorous, zinc, and iron.

Figure 18.4 White mineral salt deposits are caused by the use of hard water that has high concentrations of dissolved substances such as calcium carbonate.

Estimating Lime Deposition Potential

To calculate the lime deposition potential of irrigation water, use a similar equation to SAR. However, bicarbonate + carbonate are compared to calcium + magnesium; the number that is the least is the LDP. LDP is reported in meq/L where 1 meq/L = 50 PPM $CaCO_3$ equivalents. LDP is the lower number between the following two calculations:

Equation: LDP = (HCO_3^- + CO_3^{2-}) or (Ca^{2+} + Mg^{2+})

Example:

HCO_3^- = 4 meq/L

CO_3^{2-} = 1 meq/L

Ca^{2+} = 2 meq/L

Mg^{2+} = 1 meq/L

Results:

(HCO_3^- + CO_3^{2-}) = 4 + 1 = 5 meq/L

(Ca^{2+} + Mg^{2+}) = 2 + 1 = 3 meq/L

So, LDP = 3 meq/L (the lower one of the two)

18.6 Nutrients in Irrigation Water

Irrigation water can be an excellent source of plant nutrients. The concentrations of nutrients in irrigation water vary considerably between greenhouse operations, depending on the source of the water and the local geology. Irrigation water rarely contains high enough concentrations of the primary macronutrients (nitrogen, phosphorus, or potassium); however, water can contain significant concentrations of the secondary macronutrients—calcium, magnesium, and sulfur and micronutrients, including iron, manganese, zinc, boron, molybdenum, chlorine, copper, and nickel.

Macronutrients

Nitrate in groundwater has the potential to provide a substantial amount of plant-available nitrogen to crops. Accounting for the nitrate in irrigation water allows for substantial decreases in fertilizer costs. To measure the concentration of the irrigation water, the grower can have the nitrate content analyzed at a commercial test lab. It is important to note that results from these tests can be expressed in units of PPM NO_3^- or PPM NO_3^-–N. The more useful measurement for calculating irrigation water contribution to plant-available N is NO_3^-–N. To convert from NO_3^- to NO_3^-–N, multiply the PPM NO_3^- by 0.225. Calcium and magnesium are normally found in irrigation water. It is acceptable to use water containing high levels of calcium and magnesium. Sulfur can stress the plants, leading to reduced yield. Magnesium deficiency is common on very sandy soils with low cation exchange capacity (CEC).

Figure 21.5 Magnesium deficiency on tomatoes

Magnesium Sources

Magnesium may be supplied from magnesium sulfate, a water-soluble fertilizer that provides both magnesium and sulfur. It can also be supplied by dolomitic limestone, which is used to adjust the substrate pH. Finally, magnesium may be supplied using a commercial premixed controlled release or water-soluble fertilizer that contains magnesium. Most of these commercial premixed fertilizers use magnesium sulfate as the magnesium source, and the amount of magnesium in the fertilizer is designed to be at an appropriate ratio to the other mineral nutrients.

Sulfur

Forms of Sulfur Taken up by Plants

The sulfate (SO_4^{2-}) ion is the available form of sulfur to plants. The sulfate ion is subject to leaching too, but not as much as nitrate. The main sources of sulfate in the soil are sulfur-containing minerals and organic matter. Most sulfur, 60 to 90 percent, in soils comes from organic matter, which, upon mineralization, releases available sulfate slowly. Sulfur is, therefore, concentrated in the topsoil or plow layer.

Physiological Functions

Sulfur is essential for protein production. It promotes enzyme activation and is a component of some vitamins, improving root growth and seed production.

Sulfur Deficiency in Plants

Deficiency symptoms of sulfur are typically exhibited as yellow or pale green leaves and slow growth (Figure 21.6). Sulfur deficiency is sometimes mistaken for a shortage of nitrogen. Both nutrients have critical roles in the synthesis of protein and chlorophyll and in photosynthesis. Although the deficiency symptoms are similar, sulfur deficiency is expressed most clearly on younger leaves, whereas nitrogen deficiency is most prominent on older leaves. This difference is related to the greater mobility of nitrogen in plants; unlike sulfur, nitrogen can easily move out of older and into younger growing tissues. Sulfur-deficient leaves on some plants show interveinal chlorosis or faint striping (e.g., corn) that distinguishes them from nitrogen-deficient leaves. In addition to light green (chlorotic) young leaves, other symptoms associated with sulfur deficiency include spindly, thin stems and petioles, slow growth, and delayed maturity. Sulfur deficiency may reduce flowering.

Figure 21.6 Sulfur deficiency on cannabis

Sulfur Sources

Sulfur may be supplied in several ways. One of the most common sources is irrigation water, which may contain significant amounts of sulfur. Many substrate components contain sulfur, but the amounts vary from component to component, and not all of the sulfur in the substrate component is readily available for uptake. Field soils also contain sulfur, and if a significant amount of field soil is included in the substrate, the crop's sulfur requirement may be met. Elemental sulfur, aluminum sulfate, and iron sulfate serve as sources of sulfur. Elemental sulfur reacts and releases sulfur slowly (as a result of microbial activity) into the substrate solution, whereas aluminum sulfate

23.3 Active Plant Growth Regulator Ingredients

Before selecting a PGR, the greenhouse manager needs to understand the active ingredient (AI) in each chemical in managing greenhouse crop production. The AI is the compound in the product that can be used to increase or retard plant height, prolong or break dormancy, prolong flower and plant shelf-life, prevent leaf yellowing, abort flowers, or promote rooting, branching and/or flowering.

Ancymidol

Ancymidol can be applied to bedding plants, bulbs, chrysanthemums, Easter lilies, plugs, poinsettias, and foliage plants. Ancymidol is widely used as a foliar spray for the treatment of plants in the plug stage. Its relatively high activity and toning ability produce excellent plugs. Many growers consider ancymidol to be the product of choice for pansy production. Growers often prefer the use of ancymidol on plugs because of its lack of phytotoxicity and because its limited residual allows the plugs to grow out of the growth control effects after being transplanted, thus making it a safer PGR to apply. Ancymidol can be applied as a foliar spray or substrate drench to control plant height, specifically internode elongation, thus resulting in compact plants. Ancymidol foliar spray or substrate drench solution should be agitated to suspend the chemical in the solution, resulting in uniform distribution. Reduced efficacy may occur at increased temperatures; therefore, increased ancymidol concentration rates may be required. At higher application rates, phytotoxicity can occur as necrotic (brown, dead) spots. Vigorous plants may also require increased ancymidol concentration rates or multiple low ancymidol concentration applications. If very high ancymidol concentration rates are required, consider evaluating the use of a stronger PGR such as paclobutrazol, flurprimidol, or uniconazole to improve results and cost-effectiveness.

Benzyladenine

This AI is a synthetic cytokinin that promotes cell division and cell differentiation from undifferentiated tissues and inhibits the dominant growth of the apical meristem, which promotes axillary shoots (branching). Benzyladenine stimulates, but does not cause, an increase in branching. Therefore, the timing of the application is critical to a good branching response. Benzyladenine has been very effective in improving branching in both plugs and finished plants of many herbaceous perennial crops. Benzyladenine also delays the aging process of leaves. Optimal results occur when the plant is actively growing and is physiologically receptive for growth or flower promotion. Read the label for details on when to apply for optimum response because benzyladenine has a short period of activity and no residual in the plant. So, multiple applications may be useful with many crops. Benzyladenine does not readily move within the plant; therefore, complete coverage is required. Benzyladenine can be applied as a foliar spray or as a substrate.

Chlormequat Chloride

This active ingredient is a gibberellin inhibitor, which reduces internode elongation for a more desirable, compact plant. It is used to reduce stem elongation. Like daminozide, chlormequat chloride is a forgiving PGR that will require multiple applications. In greenhouse crops, it is most commonly used on azaleas, bedding plants, geraniums, hibiscus, poinsettias, osteospermum, and other herbaceous and woody plants. Chlormequat chloride can be applied as a foliar spray or substrate drench to control plant height, thus resulting in compact plants. Chlormequat chloride is generally applied at a rate of 200 to 3,000 PPM as a foliar spray with a maximum of three to six applications per crop cycle, depending on which product is used. Rates above 1,500 PPM often cause chlorosis on young, treated leaves of floricultural crops. Applications have the greatest effect at the beginning of rapid stem elongation. Foliar spray applications often result in phytotoxic chlorosis (yellowing) development; however, these symptoms will usually be covered by new growth. Although registered for use as a drench, it is not a cost-effective control option.

Daminozide

Used exclusively as a foliar spray, this AI is well absorbed into leaves and is a gibberellin inhibitor, reducing internode elongation for a more desirable, compact plant. Daminozide can be applied to azaleas, bedding plants, chrysanthemums, gardenias, hydrangeas, poinsettias, and other flowering and foliage plants except lilies. Notably, daminozide is highly effective in controlling bedding plant plug height and is most effective in cooler climates. In general, it is not phytotoxic and has a short-term effect that seldom results in over-stunting of treated plants. The low activity of daminozide and its lack of soil activity make it easier to get consistent, predictable responses than with the newer, more potent PGR chemistries. Plants should be well irrigated prior to treatment, but foliage should be dry at the time of treatment. Do not irrigate overhead for 18 to 24 hours after treatment.

Figure 26.2
Greenhouse with sticky cards to monitor insect activity and sticky tape strung horizontally for mass trapping.

above the plant canopy from 4 to 16 inches (10–41cm) above the top foliage. One way to easily position sticky cards is to attach each card vertically to a bamboo stake with a clothespin. As the crop grows, cards can be moved up. Alternatively, cards can be hung from above using wire or string with a binder clip tied to the end at bench level, and the height of the trap can be adjusted by tying a loop in the string or bending the wire. This method is recommended because it has the advantage of maximizing the number of insects caught while they are traveling on prevailing air currents. It is important to record the types and numbers of pests caught on the trap and to graph the results over time. When pest populations start to increase, greenhouse growers can take immediate corrective action. Growers should also look at pest population graphs after pesticide or biological control agent applications to see if the treatment was successful. This will be apparent by a large decrease in pest populations soon after treatment. If no such decrease in population occurs, it may be time to try a different pesticide or biological control agent.

Sticky Tape

Mass trapping products, such as sticky tapes, are also available for the management of thrips, whiteflies, leafminers, and fungus gnats (Figure 26.2). While sticky cards are primarily used just to alert you to insect infestations, mass trapping tools are used to reduce and manage insect infestations. Mass trapping relies on using enough surface area of the attractive sticky tapes to capture and reduce pest numbers. Sticky tape can be difficult to apply, as the rolls can be heavy and awkward. If the tape is not applied correctly, it will lead to twisting and drooping, reducing the surface area. Tape is usually used only as a post application, therefore limiting its effectiveness within the crop itself. The post row application can be very effective in stopping the migration of pests from one house to another.

Potato Disks

Potato disks are used to monitor for fungus gnat larvae. Cut a fresh potato into disks 1 inch (2.5cm) in diameter and 0.25 to 0.5 inches (0.6–1.2cm) in thickness; then press the disks into the growing medium in tagged or flagged pots. For plug trays, potatoes may be cut into small *French fry* shapes or wedges and inserted into the growing medium. In general, use 5 to 10 potato wedges per 1,000 square feet of greenhouse production area. After 2 days, inspect the undersides of the potato disks and/or wedges for the presence of fungus gnat larvae, which have distinct black head capsules. Record the number of larvae located on each potato disk or wedge and those present on the surface of the growing medium.

Indicator Plants

Indicator plants attract pests and possibly natural enemies. Many pests show a distinct preference for certain plants over other plants. Indicator plants can be more accurate than sticky cards because they give evidence of non-flying as well as flying stages of pests. It is known that some plants are more attractive to pests than others. They can be used as indicator or sentinel plants to detect pests or diseases early. Growers can use them to scout for pests quickly without having to check the whole crop. If the pest is found on an indicator plant, a grower will need to inspect nearby susceptible crop plants to determine if a management action is needed. Some common examples of indicator plants are beans for detection of two-spotted spider mites; flowering chrysanthemums for whereas *Sphaerotheca sparsa* is limited to *Asclepias.* It is important to know the identity of the fungus to determine the potential for spread to other crops that might be present in the greenhouse. Each of these fungi forms a network of hyphae over the leaf or stem surface, from which it penetrates epidermal cells to derive its nutrients.

Disease Cycle

In the greenhouse, powdery mildew fungi have a simple life cycle. Single-celled conidia (spores) form in a long chain on short, erect fungal stalks. This creates the *fluffiness* usually associated with powdery mildew. Conidia need a relative humidity of 95 percent or a near-zero vapor pressure deficit for more than 3 to 4 hours to germinate and penetrate the host's leaf or stem epidermal cells. Conidia are *powdery* and are readily disseminated by air currents in the greenhouse. After the conidia land on the plant surface, they germinate, penetrate the tissues, and send food-absorbing projections (haustoria) into the epidermal cells. Threadlike strands of the fungus (hyphae) then grow over the surface of the infected plant part and eventually produce more conidiophores and conidia. The time from when conidia land to the production of new conidia can be as short as 72 hours but is more commonly 5 to 7 days. Powdery mildew conidia are unique since, unlike most fungal spores, they do not require free moisture on plant surfaces to infect. In greenhouses, powdery mildews usually survive between crops as hyphae or fungal strands in living crop plants or in weedy hosts. Relative humidity, temperature, light, leaf wetness, and air movement (e.g., drafts) all influence the severity and spread of powdery mildew infections.

Symptoms

Powdery mildews are easily recognized by the white, powdery growth of the fungus on infected portions of the plant host (Figure 28.7). The powdery appearance results from the superficial growth of the fungus as threadlike strands (hyphae) over the plant surface and the production of chains of spores (conidia). Colonies vary in appearance from fluffy and white to sparse and gray. Powdery mildew fungi usually attack young developing shoots, foliage, stems, and flowers but can also colonize mature tissues. Symptoms often first appear on the upper leaf surface but can also develop on lower leaf surfaces. Early symptoms vary and can appear as irregular chlorotic or purple areas or as necrotic lesions, all of which are followed by the typical white, powdery appearance. Other symptoms include atypical scab-like lesions, witches'-brooms, twisting and distortion of newly emerging shoots, premature leaf coloration and drop, slowed or stunted growth, and leaf rolling. In rare but extreme situations, heavy infections cause plant death. Although diagnosis of powdery mildew is not difficult, symptoms often escape early detection if plants are not periodically monitored since symptoms can first develop on lower or middle leaves.

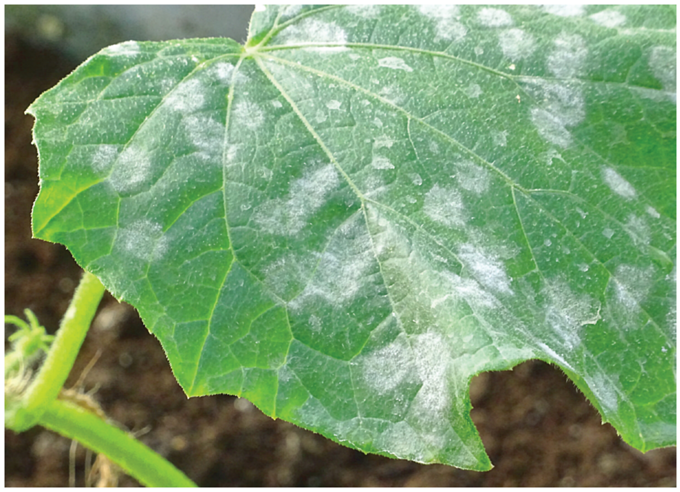

Figure 28.7 Powdery mildew on cucumbers

Cultural Management Strategies

Monitor crops on a regular basis for powdery mildew diseases. Epidemics that seem to develop overnight are often the result of undetected low-level infections that have spread spores throughout the greenhouse. Rogue infected plants or prune out diseased tissue. Perform this operation when plants are wet, or immediately place diseased material into a plastic bag to prevent spores from spreading. The use of resistant cultivars or species is a good management tactic. Although few ornamental crops have been bred for resistance, cultivars of African violet, *Begonia*, rose, pansy, *Zinnia*, *Monarda*, and *Phlox* with resistance are available. Avoid overcrowding of plants and provide good air movement. Keep relative humidity levels low in the greenhouse by a combination of heating and venting in the late afternoon and early morning. Clean the greenhouse thoroughly between crops, eliminating all weed hosts and volunteer plants.

Biorational Management Strategies

Minerals

Copper products can be very effective with minimal residue, whereas MilStop (potassium bicarbonate) can leave objectionable residue.

Chemical Management Strategies

Fungicides may be necessary when conditions are favorable for disease. Both eradicant and protectant fungicides are registered for powdery mildew control. Protectants prevent powdery mildew from developing, whereas position in the greenhouse. The spray mixture can be placed in the tank with a timer set to begin the application later. Mechanical aerosol generators generally provide good-to-excellent pesticide distribution and deposition, particularly on upper leaf surfaces. Deposition on leaf undersides has been variable, depending on the crop type, foliage canopy thickness, and plant location within the greenhouse.

30.5 Pesticide Spray Coverage

Adequate amounts of pesticide being sprayed on the target is only one aspect of efficient pesticide application. An equally important aspect is how efficiently and uniformly the target is covered. The term used to describe this is "spray coverage." The goal in spraying fungicides and insecticides should be landing as many droplets on the target as possible (maximum coverage). This is one reason why nozzles producing fine to medium droplets are preferred in general, especially when using air-assisted sprayers.

Water Sensitive Cards

The most practical and easy way to determine the location and uniformity of pesticide application is to use water-sensitive papers attached to leaves in different locations of the canopy (depth, height). These water-sensitive papers (WSP) should also be affixed to the upper side and underside of leaves (Figure 30.15). Check the coverage on these cards after spraying pesticides. Spray droplets intercepted by the yellow water-sensitive cards leave a blue stain, representing the spray deposit and coverage. No deposit on the cards indicates that the pesticide is not reaching that area of the plant. Spray coverage is usually expressed in either the percentage of the card covered with droplet stains or the number of droplet stains on one square inch of the card. Each is an important measure of spray coverage, and both should be taken into consideration when assessing spray coverage. Although the recommendation for optimum coverage varies depending on the target being sprayed (generally, fungicides require a higher coverage rate), a spray coverage of 25 to 35 percent, or 450 to 600 droplet stains per square inch of the card, represents adequate coverage for most spray applications.

When assessing the impact of any changes to the set-up of the sprayer on penetration into the crop canopy, it is a good idea only to change one thing at a time, trying to keep all other factors as constant as possible. Always try to compare like with like. For example, when assessing the impact of increasing the application volume, try to do this with nozzle types that produce the same spray quality at a similar pressure; this way, one is comparing the effect of total application volume, not other factors. A similar approach can be taken to assess the impact of spraying speed or spray quality (droplet size).

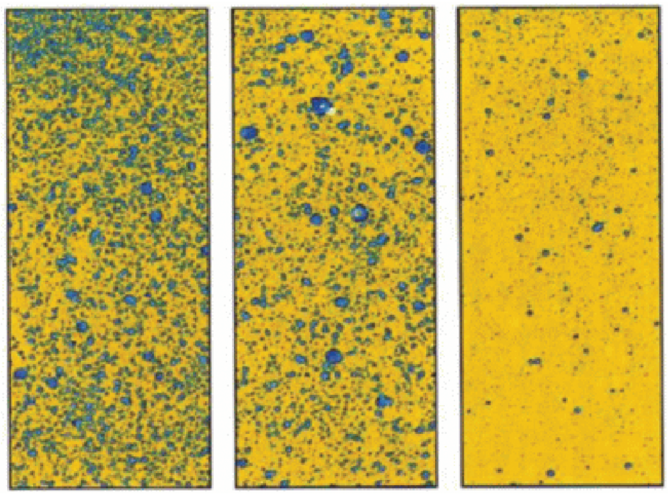

Figure 30.15 Water sensitive cards used for assessing spray coverage.

Image Processing Software for Analysis of Droplets

The use of water-sensitive papers is an important tool for assessing the quality of pesticide application on crops, but manual analysis is laborious and time-consuming. Instead, image processing software is becoming the standard in analyzing the spray deposition on the WSP using artificial intelligence, i.e., machine learning and machine vision. This requires a camera or scanner to produce a digital image of the WSP and specialized analytical software to extract the relevant data using artificial intelligence. DepositScan, offered by USDA, consists of a set of custom plugins that are used by an image-processing program to produce a number of measurements useful for expressing spray deposit distribution. The program then reports coverage, the total number of droplets deposited, and deposition volume, giving rapid feedback on application performance. Apps are also available that will quickly and easily analyze water-sensitive cards for coverage. SnapCard is an app that is available only for Android smart devices. SmartSpray, is available for both iOS and Android smart devices. These apps can be used to optimize spray coverage, reduce spray drift, and minimize the risk of resistance development in target pest populations.

Machine Vision Image Training Datasets

Common to all computer vision-based precision agriculture tasks is presumably the goal of detecting the objects of interest (e.g., crop, weed, or fruit) and discriminating them from the rest of the scene. Achieving this requires, in addition to a well-designed hardware system, a robust data analysis pipeline that generally involves training machine learning models with specific image datasets. A high-quality, large-scale machine vision dataset is vital to the performance of the developed data analysis pipeline and the success of the end task. Machine vision image training datasets are image collections, often accompanied by metadata or annotations, designed for training and evaluating machine learning algorithms, particularly in computer vision. These datasets are essential for object detection, image classification, semantic segmentation, and more tasks.

Image Annotation

Image annotation in agriculture is an essential process that involves labeling objects and features in images. It provides contextual information that aids machine learning models in recognizing patterns and making accurate predictions. Data labeling is crucial for training AI/ML systems to identify, analyze, and optimize various aspects of agricultural practices. The annotation of images where crops are affected by diseases or pests plays a crucial role in enabling early detection and facilitating targeted intervention strategies. The bounding box annotation is a technique that helps identify and locate specific elements by drawing rectangular boxes around objects of interest, such as crops, weeds, insects, or equipment within an image, enabling precise object detection and localization (Figure 31.2).

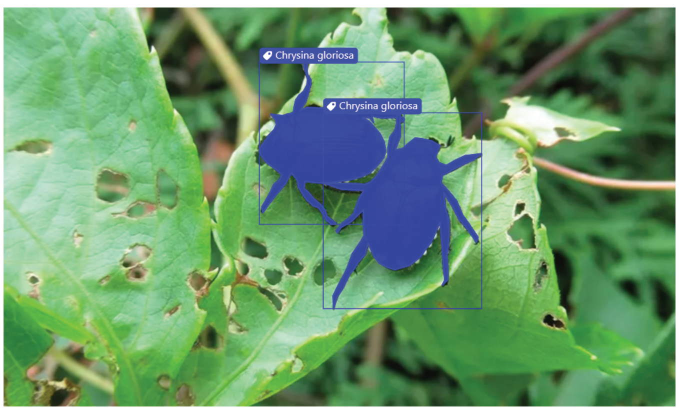

Figure 31.2 Bounding box annotation

31.4 Robotics

In recent years, agricultural robotics has received significant attention in research studies, being considered a way to address some important issues of the greenhouse sector, such as precision agriculture, resource saving, improvement of safety conditions, and shortage of human labor. These issues are particularly relevant in greenhouse production systems, where humans still require many highly repetitive and sometimes dangerous operations. Generally, a prominent human workforce is needed in greenhouses. The cost allocated to manual labor is the most significant factor: more than 30 percent of the total production costs are spent on wages by the grower for employees. In addition, the availability of a skilled workforce that accepts repetitive tasks in uncomfortable greenhouse conditions is decreasing rapidly, causing a reduced availability of workforce. On this basis, greenhouse agriculture lends itself well to automation. In particular, the use of robotics in greenhouse agriculture would allow an increase overall performance and production efficiency, improving, at the same time, labor quality and safety. Robots can efficiently perform repetitive tasks, replacing human labor, and, at the same time, can operate in a hazardous environment, thereby strongly reducing the exposure of human operators to risks, such as spraying chemicals and pesticides in protected cultivation. Thus, through the development of automation in greenhouses, it is possible to guarantee better working conditions, protect workers from physical and chemical hazards, and improve their comfort, and safety.

Common Types of Robots

As robotics manufacturers continue to deliver innovations across capabilities, price, and form factor, robotics solutions are being implemented in an ever-increasing number of applications in agriculture. Advancements in processing power and AI capabilities mean that we can now use robots to fulfill critical purposes in a plethora of ways. Today's robots can generally be grouped into four categories.

Autonomous Mobile Robots (AMRs)

An autonomous mobile robot is a type of robot that can understand and move through its environment independently. AMRs use a sophisticated set of sensors, artificial intelligence, and machine learning and compute for path planning to interpret and navigate through their environment, untethered from wired power. Because AMRs are equipped with cameras and sensors, if they experience an unexpected obstacle while navigating their environments, such as a fallen box or a crowd of people, they will use a navigation technique like collision

Greenhouse Management

Updated and revised to keep pace with developments, the third edition of ***Greenhouse Management*** is meant to be a stand-alone resource guide that describes all phases of greenhouse management. This book is written in a non-technical format designed to be practical and well-suited guide for growers, technical industry representatives, and university horticulture students.

New and Key Features of the Third Edition:

- New chapters on greenhouse curtains and artificial intelligence in greenhouses
- A better introduction to greenhouse lighting
- Updated information on growing media
- Expanded coverage on irrigating greenhouse crops and micro-irrigation systems
- A dedicated chapter on greenhouse water treatment and filtration
- Revised and expanded information on fertigation
- Expanded coverage on plant nutrition of greenhouse crops
- Revised and expanded information on pesticide application
- A number of important appendices have been added

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