3

The Propagation Environment

INTRODUCTION

Propagation can be done in the field, orchard, forest, outdoor raised beds, and in protected culture environments such as greenhouses, poly-covered houses, and tissue culture laboratories. The plant propagation period is generally a very narrow segment of a plant's life, ranging from several weeks for fast-growing herbaceous plants to one to two years for woody perennials. Following propagation, the rooted cuttings, seedlings **(plugs), layers,** or tissue culture produced plants are transplanted as **liner plants.** The liner plants are grown in small pots and then transplanted into larger containers or directly transplanted into field production. In other production systems plants may be propagated and produced in the same container or field location without going through a liner stage.

plugs Small seedling plants.

layers Plants produced asexually from layering, such as air layering or stooling.

To enhance the propagation of plants, commercial producers manipulate the environment of **propagules** (cuttings, seeds) by managing:

a. **microclimatic conditions** (light, water-relative humidity, temperature, and gases)
b. **edaphic factors** (propagation medium or soil, mineral nutrition and water), and
c. **biotic factors**—interaction of propagules with other organisms (such as beneficial bacteria, mycorrhizal fungi, pathogens, insect pests, etc.) (Fig. 3–1).

propagule A plant structure used for regenerating plants, which can include cuttings, seeds, grafts, layers, tissue culture explants, and single cells.

microclimatic conditions Any environmental factors (relative humidity, temperature, light, gases, etc.) in the immediate vicinity of the propagule during propagation.

edaphic factors Any factors influenced by the soil or propagation medium (substrate).

Unique ecological conditions exist during propagation. Commercial propagators may have to compromise to obtain an "average environment" in

learning objectives

- Identify the environmental factors affecting propagation.
- Describe the physical structures for managing the propagation environment.
- Describe the containers for propagating and growing young liner pots.
- Discuss the management of media and nutrients in propagation and liner production.
- Discuss the management of microclimatic conditions in propagation and liner production.
- Discuss the management of biotic factors—pathogens and pests—in plant propagation.
- Explain the post-propagation care of liners.

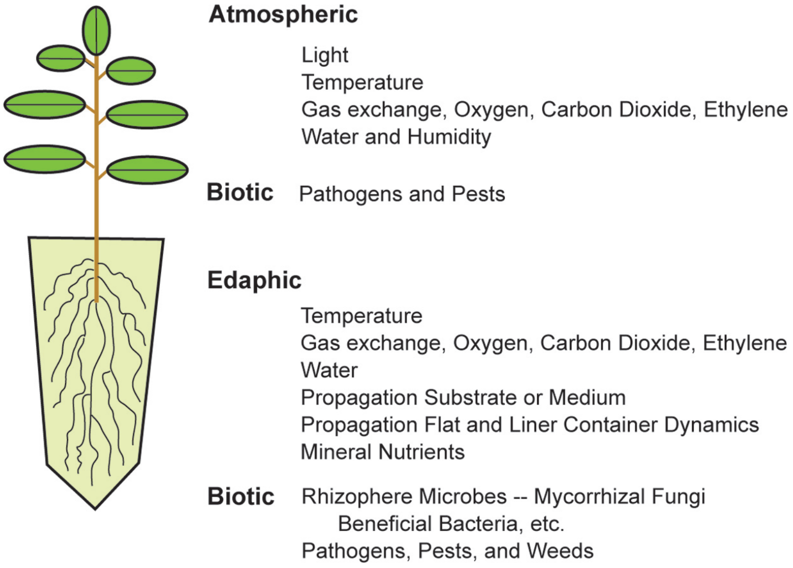


Figure 3–1
The propagation environment: Manipulation of microclimatic, edaphic, and biotic factors. Modified from Landis (70).

Shading Partial reduction of light to 100 percent light exclusion that can occur during stock plant manipulation and/or propagation

hardening-off The stress adaptation process or **acclimation** that occurs as a propagule, such as a cutting, is gradually weaned from a high to a low relative humidity environment during rooting; in **micropropagation** (tissue culture) acclimation is referred to as **acclimatization.**

which a whole range of species are propagated by cuttings, seed, and/or tissue culture explants (69). The environmental conditions that are optimum for plant propagation are frequently conducive for pests (pathogenic fungi, viruses, bacteria, insect, and mite development). Astute propagators not only manage the environment during propagation, but also manipulate the environment of **stock plants** prior to selecting propagules, such as **shading** and stooling to maximize rooting potential of a propagule; and post propagation—**hardening-off** (weaning rooted cuttings from the mist system and changing fertility regimes) to assure growth and survival of tender-rooted liner plants after propagation.

ENVIRONMENTAL FACTORS AFFECTING PROPAGATION

In propagating and growing young nursery plants, facilities and procedures are designed to optimize the response of plants to environmental factors influencing their growth and development, such as **light, water, temperature, gases,** and **mineral nutrition.** In addition, young nursery plants require protection from pathogens and other pests, as well as control of salinity levels in the growing media. The propagation structures, equipment, and procedures described in this chapter, if handled properly, maximize the plants' growth and development by controlling their environment.

BOX 3.1 GETTING MORE IN DEPTH ON THE SUBJECT
LINER PRODUCTION

A **liner** traditionally refers to lining out nursery stock in a field row. The term has evolved to mean a small plant produced from a rooted cutting, seedling, plug, or tissue culture plantlet. **Direct sticking** or **direct rooting** into smaller **liner pots** is commonly done in United States propagation nurseries. Seedlings and rooted cuttings can also be transplanted into small liner pots and allowed to become established during liner production, before being transplanted to larger containers **(upcanned)** or outplanted into the field.

BOX 3.2 GETTING MORE IN DEPTH ON THE SUBJECT

MEASUREMENT OF LIGHT

Irradiance is the relative amount of light as measured by radiant energy per unit area. Irradiance, intensity, and photon flux all measure the amount of light very differently; they are not interchangeable terms. **Photosynthetic photon flux (PPF)** is the best light measurement for plant propagation, since the process of photosynthesis relies on the number of photons intercepted, not light given off by a point source (intensity) or energy content (irradiance). **Photosynthetic active radiation (PAR)** is measured in the 400 to 700 nanometer (nm) waveband as PPF in micromoles of photons per unit area per time (µmol m^{-2}s^{-1}) with a **quantum sensor** or as watts per square meter (W/m^2) with a **pyranometric sensor.** Some propagators still measure light intensity with a **photometric sensor,** which determines foot-candles or lux (1 foot-candle = 10.8 lux). A photometric sensor is relatively insensitive to wavelengths that are important for plant growth; that is, it may record high light intensity from an artificial electric light source, but it does *not* take into account if the light source is rich in green and yellow, or poor in red and blue light—which would lead to poor plant growth. Quantum and radiometric (pyranometer) sensors can be purchased from instrument companies (i.e., LI-COR Biosciences, www.licor.com; or Apogee Instruments, Inc., www.apogee-inst.com). For determining **light quality** or **wavelength,** the spectral distribution is measured with a portable spectroradiometer, which is a very expensive piece of equipment.

Light

Light is important for photosynthesis as a source of radiant energy. Light also generates a heat load that needs to be controlled (i.e., too high a temperature can quickly desiccate and kill cuttings). The management of light can be critical for rooting cuttings, germinating seeds, growing seedlings, or shoot multiplication of **explants** during tissue culture propagation. Light can be manipulated by controlling *irradiance* (see Box 3.2), *light duration* (daylength, photoperiod), and *light quality* (wavelength). For a relative comparison of light units for propagation, see Box 3.3 on page 52.

Irradiance While many propagators still measure light intensity, determining the photon flux of light is more accurate because the process of photosynthesis depends on the number of photons intercepted (*photosynthetic photon flux*), not just the light given off by a point source (*intensity*).

Daylength (Photoperiod) Higher plants are classified as long-day, short-day, or day-neutral, based on the effect of photoperiod on initiation of reproductive growth. **Long-day** plants, which flower chiefly in the summer, will flower when the **critical photoperiod** of light is equaled or exceeded; **short-day** plants, such as chrysanthemums, flower when the critical photoperiod is not exceeded. Reproductive growth in **day-neutral** plants, such as roses, is not triggered by photoperiod. The discovery of *photoperiodism* by Garner and Allard demonstrated that the dark period, not the light period, is most critical to initiation of reproductive growth, even though light cycles are traditionally used to denote a plant's photoperiod. In propagation, fresh seed collected in the fall from selected woody plant species, such as *Larix,* need long-day conditions to germinate. Dahlia cuttings need short-day conditions to trigger tuberous root formation.

Photoperiod can be extended under short-day conditions of late fall and early winter by lighting with incandescent lights, or high intensity discharge lights (HID) (Fig. 3–14, page 65). Conversely, photoperiod can be shortened under the long-day conditions of late spring and summer by covering stock plants and cuttings with black cloth or plastic that eliminates all light. See the in-depth discussion of phytochrome and photoperiodism in Chapter 7.

Light Quality Light quality is perceived by the human eye as color, and corresponds to a specific range of wavelengths. Red light is known to enhance seed germination of selected lettuce cultivars, while far-red light inhibits germination. Far-red light can promote bulb formation on long-day plants, such as onion (*Allium cepa*). Blue light enhances in vitro bud regeneration of tomato (77). Using greenhouse covering materials with different spectral light-transmitting characteristics, researchers at Clemson University (97) have been able to control the height and development of greenhouse-grown plants, rather than relying on the chemical application of growth regulators for height control. This has application for plant propagation, liner production, and plant tissue culture systems. Red shade cloth shifts light quality towards the blue/green and is being used to enhance root development of cuttings (Fig. 3–11, page 62). Red shade cloth can also be used to increase leaf surface and branching, which is important in liner development (111).

BOX 3.3 **GETTING MORE IN DEPTH ON THE SUBJECT**

RELATIVE COMPARISON OF LIGHT UNITS FOR SOLAR RADIATION AND ARTIFICIAL LIGHTING (67, 72, 117)*

Light Source	Energy [Photosynthetic photon plux] (μmol $m^{-2}s^{-1}$)	Radiation [Irradiance] (watts m^{-2})	Illumination [Light intensity] (lux)	Illumination [Light intensity] (ft-candles)
Solar Radiation				
Full sunlight	2,000	450	108,000	10,037
Heavy overcast	60	15	3,200	297
Artificial Light Source				
Metal halide (400 W) lamp @ 2 m height	19	4	1,330	124

*Photosynthetically active radiation (PAR): 400 to 700 nm. Conversions between energy, radiation, and illumination units are complicated and will be different for each light source. The spectral distribution curve of the radiant output must be known in order to make conversions.

Water-Humidity Control

Water management and humidity control are critical in propagation. Water management is one of the most effective tools for regulating plant growth. Evaporative cooling of an **intermittent mist** system can help control the propagation house microenvironment and reduce the heat load on cuttings, thereby permitting utilization of high light conditions to increase photosynthesis and encourage subsequent root development. A solid support medium, such as peat-perlite, is not always necessary to propagate plants; peach cuttings can be rooted under aeroponic systems, while woody and herbaceous ornamentals can be rooted in modified, aero-hydroponic systems without relying on overhead mist (108). Tissue culture explants are often grown in a liquid phase rather than on a solid agar media.

intermittent mist A thin film of water produced through a pressurized irrigation system that cools the atmosphere and leaf surface of cuttings.

While leaf **water potential** (Ψ_{leaf}) is an important parameter for measuring water status of seedlings and cuttings, and influences rooting of cuttings, **turgor** (Ψ_p) is physiologically more important for growth processes. The water status of seedlings and cuttings is a balance between transpirational losses and uptake of water. Later in this chapter the methods to control water loss of leaves of cuttings, seedlings, and containerized grafted plants are discussed.

BOX 3.4 **GETTING MORE IN DEPTH ON THE SUBJECT**

PLANT WATER MEASUREMENTS IN PROPAGATION

Water potential (Ψ_{water}) refers to the difference between the activity of water molecules in pure distilled water and the activity of water molecules in any other system in the plant. Pure water has a water potential of zero. Since the activity of water in a cell is usually less than that of pure water, the water potential in a cell is usually a negative number. The magnitude of water potential is expressed in megapascals [1 megapascal (MPa) = 10 bars = 9.87 atmospheres]. Propagators can determine water potential by using a pressure chamber (pressure bomb) manufactured by PMS Instrument Company (www.pmsinstrument.com) or Soil Moisture Corporation (www.soilmoisture.com). A psychrometer with a microvolt meter (LiCor, www.licor.com) can also be used. Estimation of **turgor** (Ψ_p) (or pressure potential) requires measurement of **water potential** (Ψ_{water}) minus the **osmotic potential** (Ψ_π), which is based on the formula $\Psi_{water} = \Psi_p + \Psi_\pi$. Osmotic potential can also be determined by either a pressure chamber or a psychrometer. The matrix potential (Ψ_m) is generally insignificant in determining Ψ_{water} but is important in seed germination. See the discussion on water potential and seed germination in Chapter 7.

Temperature

Temperature affects plant propagation in many ways. Seed dormancy is broken in some woody species by cool-moist stratification conditions that allow the germination process to proceed. Temperature of the propagation medium can be suboptimal for seed germination or rooting due to seasonally related ambient air temperature or the cooling effect of mist. In grafting, heating devices are sometimes placed in the graft union area to speed up graft union formation, while the rest of the rootstock is kept dormant under cooler conditions (see Fig. 12–48).

It is often more satisfactory and cost-effective to manipulate temperature by bottom heating at the propagation bench level, rather than heating the entire propagation house (Fig. 3–2). The use of heating and cooling systems in propagation structures is discussed further in this chapter (see Chapter 10 for heating equipment and sensors).

Gases and Gas Exchange

High respiration rates occur with seed germination and plug development, and during adventitious root formation at the base of a cutting. These aerobic processes require that O_2 be consumed and CO_2 be given off by the propagule. Seed germination is impeded when a hard seed coat restricts gas exchange. Likewise, gas exchange at the site of root initiation and subsequent rooting are reduced when cuttings are stuck in highly water-saturated propagation media with small air pore spaces. In leaves of droughted propagules, stomata are closed, gas exchange is limited, and suboptimal rates of photosynthesis occur. During propagation in enclosed greenhouses, ambient CO_2 levels can drop to suboptimal levels, limiting photosynthesis and propagule development. The buildup of ethylene gas (C_2H_4) can be deleterious to propagules during storage, shipping, and propagation conditions. Ethylene also plays a role in plant respiration, rooting of cuttings, and seed propagation.

Mineral Nutrition

To avoid stress and poor development during propagation, it is important that the stock plants be maintained under optimal nutrition—prior to harvesting propagules. During propagation, nutrients are generally applied to seedlings and plugs by **fertigation** (soluble fertilizers added to irrigation water) or with controlled-release fertilizers that are either

fertigation The application of soluble fertilizer during the irrigation of a seedling or rooted cutting.

Figure 3–2 Propagation house heating systems. (a) Gas-fired infrared or vacuum-operated radiant heaters (arrow). (b) Forced hot air heating system. (c) Greenhouse, hot water boilers. (d) Heating below the bench for better control of root zone temperature.

preincorporated into the propagation medium or broadcast **(top-dressed)** across the medium surface. Cuttings are normally fertilized with a controlled-release fertilizer preincorporated into the propagation medium (which is discussed later in this chapter and in Chapter 10) or with soluble fertilizer applied *after* roots are initiated. The development of intermittent mist revolutionized propagation, but the mist can severely leach cuttings of nutrients. This is a particular problem with cuttings of difficult-to-root species that have long propagation periods.

PHYSICAL STRUCTURES FOR MANAGING THE PROPAGATION ENVIRONMENT

Propagation Structures

Facilities required for propagating plants by seed, cuttings, and grafting, and other methods include two basic units. One is a structure with temperature control and ample light, such as a greenhouse, modified quonset house, or hotbed—where seeds can be germinated, or cuttings rooted, or tissue culture microplants rooted and acclimatized. The second unit is a structure into which the young, tender plants (liners) can be moved for hardening, which is preparatory to transplanting outdoors. Cold frames, low polyethylene tunnels or sun tunnels covered by Saran, and lathhouses are useful for this purpose. Any of these structures may, at certain times of the year and for certain species, serve as a propagation and acclimation structure. A synopsis of how structures are utilized in propagation is presented in Table 3–1.

Aseptic Micropropagation Facilities

Aseptic micropropagation facilities are described in Chapter 18.

Greenhouses

Greenhouses have a long history of use by horticulturists as a means of forcing more rapid growth of plants (11, 41, 55, 75, 122). Most of the greenhouse area in

Table 3–1
Utilization of Propagation Structures

Propagation structure	Micropropagation	Cuttings	Seedlings/ Plugs	Grafting	Layering	Liner production and hardening-off
Micropropagation facilities (indoor)	Yes	No; except microcuttings	No	No; except micrografting	No	No
Greenhouses	Yes; during acclimatization	Yes	Yes	Yes	Yes; air layering	Yes
Closed-case propagation	No	Yes	Yes	Yes	No	Yes
Hot frames (hotbeds)						
Heated sun tunnels						
Closed-case propagation	No; except acclimatization	Yes; hardwood and semi-hardwood cuttings	Yes	Yes	Yes	Yes
Cold frames						
Unheated sun tunnels						
Lathhouses (shade houses)	No; except acclimatization	Yes; hardwood and semi-hardwood cuttings	Yes	Yes	Yes	Yes; used extensively for this
Miscellaneous closed-case propagation systems in greenhouses: (a) Propagating frames (b) Contact polyethylene systems	No; except acclimatization	Yes; hardwood and semi-hardwood cuttings	Yes	Yes; sometimes with bench grafting and acclimation	No	Yes

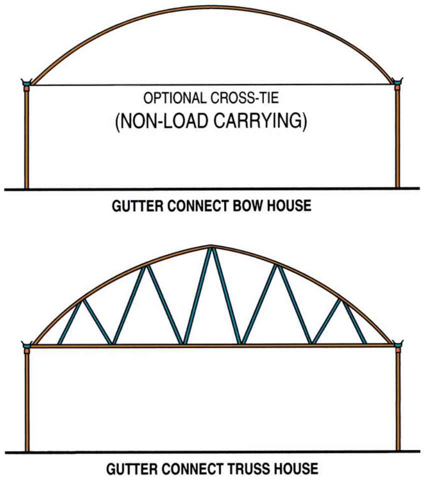
the United States is used for the wholesale propagation and production of floricultural crops, such as pot plants, foliage plants, bedding plants, and cut flowers; fewer are used for nursery stock and vegetable crops (104).

Greenhouse structures vary from elementary, home-constructed to elaborate commercial installations. Commercial greenhouses are usually independent structures of even-span, **gable-roof construction,** proportioned so that the space is well utilized for convenient walkways and propagating benches (55). In larger propagation operations, several single greenhouse units are often attached side by side, eliminating the cost of covering the adjoining walls with glass or polyethylene (Fig. 3–3). These gutter-connected houses, while more expensive to construct than independent ground-to-ground structures, allow easy access between houses and decrease the square footage (meters) of land needed for propagation houses. Heating and cooling equipment is more economical to install and operate, since a large growing area can share the same equipment (62). Greenhouses with double-tiered, moveable benches that can be rolled outside, and **retractable roof** greenhouses reduce energy costs (Figs. 3–4 and 3–5); they are being used in cutting and

gable-roof constructed greenhouse A unit that has more expensive, reinforced upper support for hanging mist systems, supplementary lights, or additional tiers of potted plants.

retractable roof greenhouse A unit with a roof that can be opened during the day and closed at night.

(a)

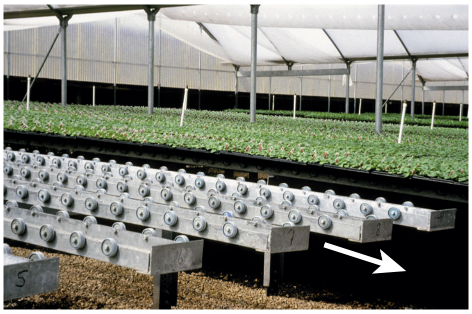


(b)

(c)

(d)

Figure 3–3
Gutter-connected propagation greenhouses. (a) A series of gutter-connected propagation houses. (b) The basic types of gutter-connected propagation greenhouses: bow or truss. Bows are less expensive, but offer less structural strength. Trusses make for a stronger house, while giving propagators the ability to hang plants and equipment, such as monorails, curtain systems, and irrigation booms. (c) Non—load-carrying bow propagation house. (d) Load-bearing, gutter-connected truss house (arrow).


(a)


(b)


(c)

(d)


(e)

Figure 3–4
(a and b) Instead of a movable bench, propagation trays are placed on rollers; notice how all trays on rollers slant toward the middle of the propagation house for easier movement of materials. (c) Movable benches for seedling plug production. (d and e). Propagation house with retractable benches, which can be rolled from the greenhouse structure to the outdoors, have reduced energy costs. (d) Inside of house with double-tiered benches that can be brought in at night and during inclement weather. Benches slide through opening of greenhouse and can be left outside under full sun conditions.


(a)


(b)


(c)


(d)

Figure 3–5
(a, b, and c) Retractable roof greenhouse for reducing heat load during propagation and liner production, and (d) a top-vented Dutch-style glasshouse with thermal curtains (arrow) for shade and trapping heat during winter nights.

seed propagation, and seedling plug production. Since the liner seedlings are partly produced under full sun conditions, they are better acclimatized for the consumer (8).

Quonset-type greenhouse An inexpensive propagation house made of bent tubing or PVC frame that is covered with polyethylene plastic.

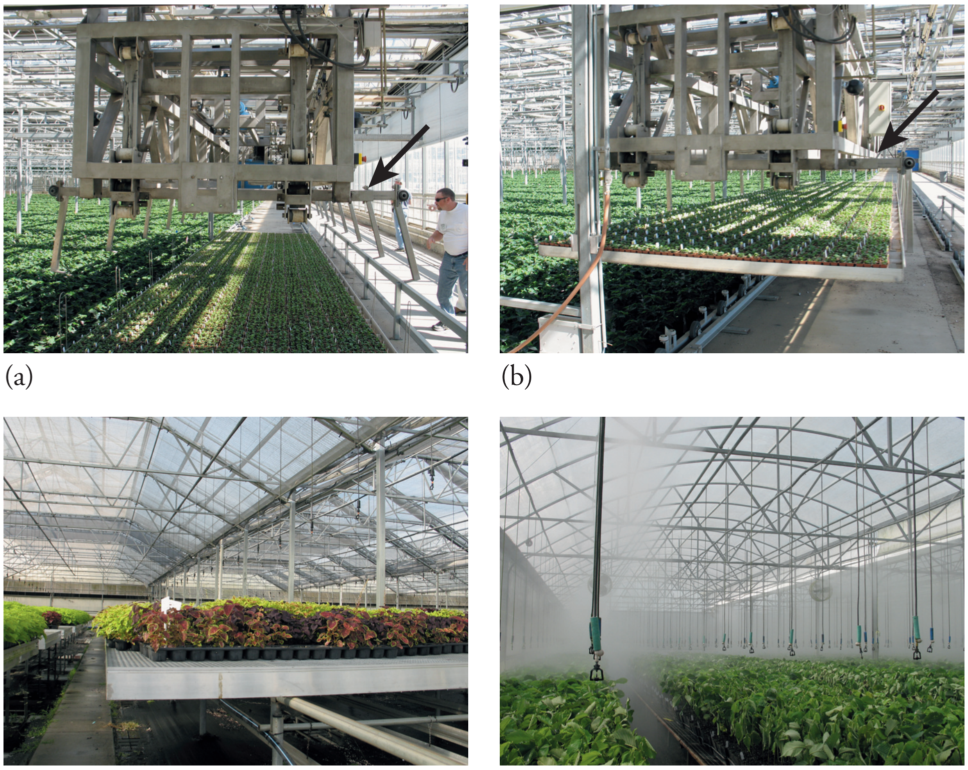
Quonset-type construction is very popular. Such houses are inexpensive to build, usually consisting of a framework of piping, and are easily covered with one or two layers of polyethylene (Fig. 3–6).

Arrangement of benches in greenhouses varies considerably. Some propagation installations do not have permanently attached benches, their placement varying according to the type of equipment, such as lift trucks or electric carts, used to move flats and plants. The correct bench system can increase production efficiency and reduce labor costs (124). Rolling benches can reduce aisle space and increase the usable space by 30 percent in a propagation greenhouse. The benches are pushed together until one needs to get between them, and then rolled apart (Fig. 3–4). With rolling benches, propagation work can be done in an ergonomically correct fashion, making workers more comfortable, efficient, and productive (118). Besides increased propagation production numbers, rolling benches allow other automation features to be added (Fig. 3–7). Conversely, to reduce costs, many propagation houses are designed not to use benches, but rather cutting flats or small liner containers are placed on the gravel or Saran-covered floor (Figs. 3–6 and 3–7). It all depends on the propagation system and units to be produced.

In an **floor ebb and flood system (flood floor),** greenhouse benches are eliminated and plants are produced with an automated floor watering and fertility system. There are below-ground floor-heating pipes and irrigation lines, a system of runoff-capturing tanks

(a) (b) (c) (d)

Figure 3–6
Versatility of a polyethylene, saran-shaded quonset house. (a) Propagators sticking cuttings into rooting media floor beds previously prepared and sterilized with methyl bromide. (b) Cuttings in small liner rooting pots under mist. (c) Rooted liner crop protected under saran shade with poly sidewalls, and (d) shade removed and rooted liner crop ready for transplanting and finishing off in larger container pots.



(a) (b) (c) (d)

Figure 3–7
For more efficient use of costly greenhouse propagation space, movable benches on rollers have been installed to reduce aisle space. (a and b) Hydraulic lift system (arrow) to pick up and move benches. (c) Movable benches for maintaining coleus stock plants. (d) To eliminate bench space, cuttings in liner pots are placed on the cement propagation house floor and intermittent mist is applied from mist nozzles suspended from the ceiling.

with filters, and computer-controlled return of appropriate levels of irrigation water mixed with soluble fertilizer to the floor growing area (9, 89). While this has received limited use in the propagation of plants, it does have application for liner stock plant production of seedling plugs, rooted cuttings, and tissue culture produced plantlets (Fig. 3–8). Flood floor systems are more efficient than conventional bench greenhouses. They are highly automated, require less labor, and are environmentally friendly—since irrigation runoff, including nutrients and pesticides, is recaptured and recycled. The drawback of these benchless systems is the potential for rapid disease spread.

Greenhouse construction begins with a metal framework covered with polycarbonate, acrylic, glass, or poly (plastic) material. Gutter-connected greenhouses can be constructed as bow-style houses, which are less expensive and offer less structural strength, or as load-bearing truss-style houses, which give propagators the ability to hang mist and irrigation booms, install ceiling curtains for temperature and light control, and so on (Fig. 3–3). All-metal prefabricated greenhouses with prewelded or prebolted trusses are also widely used and are available from several manufacturers.

In any type of greenhouse or bench construction using wood, the wood should be pressure-treated with a preservative such as chromatid copper arsenate (CCA), which will add many years to its life (5). The two most common structural materials for greenhouses are steel and aluminum. Most greenhouses are made from galvanized steel, which is cheaper, stronger, lighter, and smaller than an aluminum member of equal strength. Aluminum has rust and corrosion resistance, and can be painted or anodized in various colors (62). With the high cost of

BOX 3.5 **GETTING MORE IN DEPTH ON THE SUBJECT**

SOURCES OF COMMERCIAL GREENHOUSES

For sources of commercial greenhouses, contact the National Greenhouse Manufacturers Association (www.ngma.com). A number of trade journals such as *GrowerTalks* (www.ballpublishing.com, choose the link for GrowerTalks) and *Greenhouse Beam Pro* (www.greenbeampro.com) list commercial greenhouse manufacturers and suppliers that include greenhouse structures, shade and heat retention systems, cooling and ventilation, environmental control computers, bench systems, and internal transport systems in greenhouses.

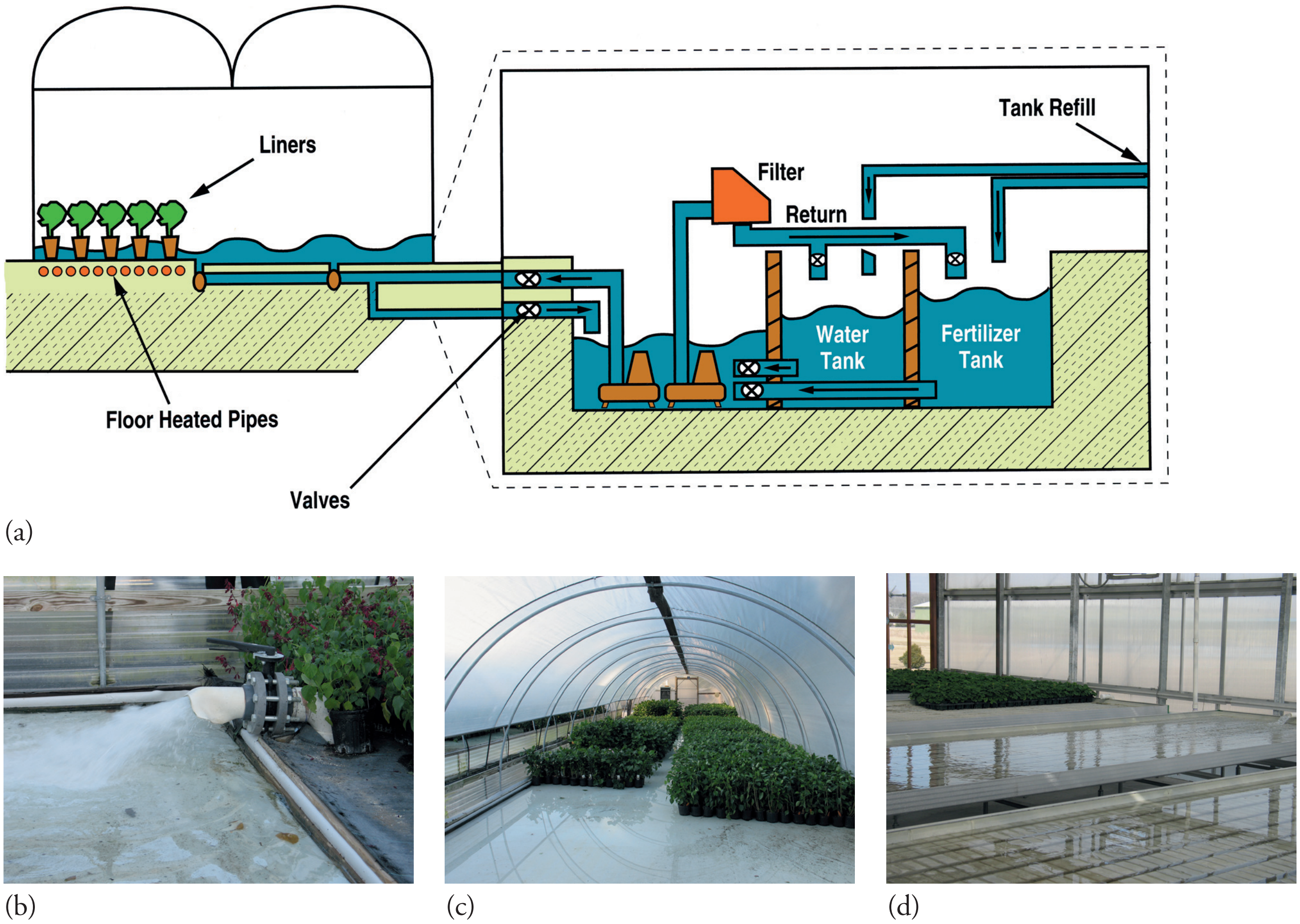


Figure 3–8
(a, b, and c) An ebb and flood or flood floor system. No benches are used and stock plants are produced with an automated floor watering and fertility system. There are below-ground floor heating pipes and irrigation lines, a system of runoff-capturing tanks with filters, and computer-controlled return of appropriate levels of irrigation water mixed with soluble fertilizer to the floor growing area. (a) Schematic of ebb and flood system with liner plants. (b and c) Flood floor system for maintaining stock plants. (d) Ebb and flood bench system.

lumber, fewer greenhouses are constructed with wood, and traditional wooden benches are being replaced by rigid plastics, metal benches, and other synthetic materials.

Greenhouse Heating and Cooling Systems

Ventilation, to provide air movement and air exchange with the outside, is necessary in all greenhouses to aid in controlling temperature and humidity. A mechanism for manual opening of panels at the ridge and sides or with passive ventilation can be used in smaller greenhouses, but most larger installations use a forced-air fan and pad-cooling ventilation system either regulated by thermostats or controlled by computer (42, 89).

Traditionally, greenhouses have been heated by steam or hot water from a central boiler through banks of pipes (some finned to increase radiation surface) suitably located in the greenhouse (Fig. 3–2). Unit heaters for each house, with fans for improved air circulation, are also used. If oil or gas heaters are used, they must be vented to the outside because the combustion products are toxic to plants (and people!), and ethylene gas generated can adversely affect plant growth. In large greenhouses, heated air is often blown into large—30 to 60 cm (12 to 24 in)—4-mil convection polyethylene tubes hung overhead. These extend the length of the greenhouse. Small—5 to 7.5 cm (2 to 3 in)—holes spaced throughout the length of these tubes allow the hot air to escape, thus giving uniform heating throughout the house. These same convection tubes can be used for forced-air ventilation and cooling in summer, eliminating the need for manual side and top vents.

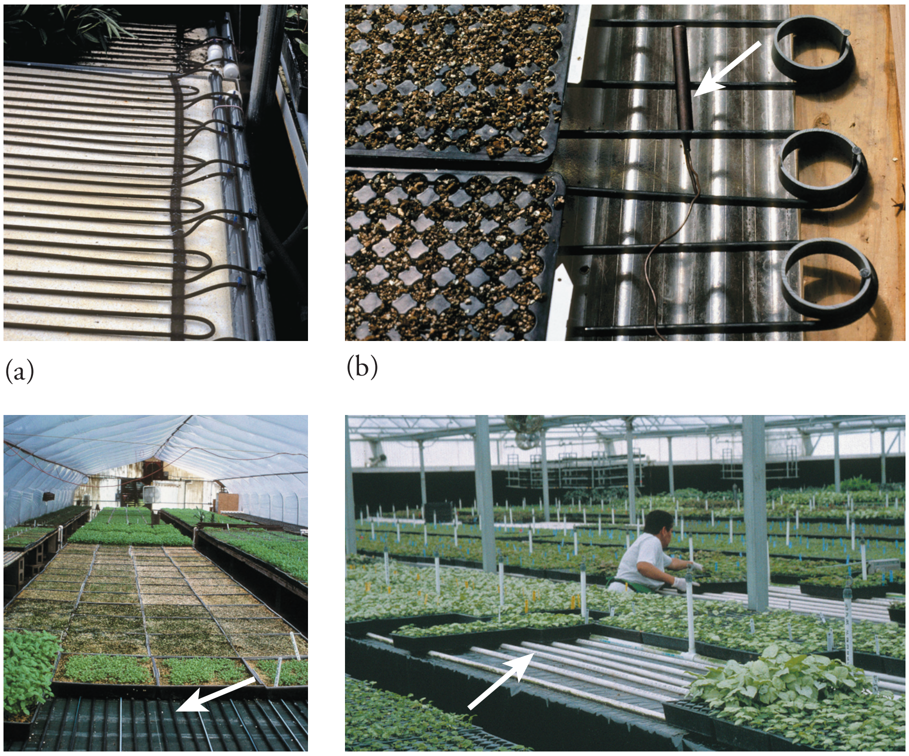
Gas-Fired Infrared Heaters **Gas-Fired infrared heaters** are vacuum-operated radiant heaters that are sometimes installed in the ridges of greenhouses with the concept of heating the plants but not the air mass. Infrared heaters consist of several lines of radiant tubing running the length of the house, with reflective shielding above the tubes installed at a height of 1.8 to 3.7 m (6 to 12 ft) above the plants (Fig. 3–2). The principal advantage of infrared heating systems in greenhouses is lower energy use. Cultural practices may need to be changed because infrared heating heats the plant but not the soil underneath.

gas-fired infrared heaters Vacuum-operated radiant heaters installed in the ridges of greenhouses with the concept of heating the plants but not the air mass.

Root Zone Heating In contrast to infrared heating, root zone heating is done by placing pipes on or below the soil surface in the floor of the greenhouse, or on the benches, with recirculating hot water—controlled by a thermostat—circulating through the pipes. This places the heat below the plants, which hastens the germination of seeds, rooting of cuttings, or growth of liner plants. This popular system has been very satisfactory in many installations, heating the plants' roots and tops, but not the entire air mass in the greenhouse, yielding substantial fuel savings. It is also excellent for controlling foliage diseases. The majority of propagation (seed germination, rooted cuttings, and plug growing) is done with some form of root zone heat (Figs. 3–2 and 3–9) (55).

Solar Heating Conservation of energy in the greenhouse is important (83). In greenhouses, solar heating occurs naturally. The cost of fossil fuels has evoked considerable interest in methods of conserving daytime solar heat for night heating (50, 64). Conservation methods need to be developed and utilized; otherwise, high heating costs may eventually make winter use of greenhouses in colder regions economically unfeasible—relegating greenhouse operations to areas with relatively mild winters (89, 122).

Most heat loss in greenhouses occurs through the roof. One method of reducing heat loss in winter is to install sealed polyethylene sheeting outside over the glass or fiberglass covered structure, or to use two layers of polyethylene sheeting, as in a quonset house. This double-poly method of insulation is very effective. The two layers are kept separate by an air cushion from a low-pressure blower. Energy savings from the use of this system are substantial—more than 50 percent reduction in fuel compared to conventional glass greenhouses—but the greatly lowered light intensity with the double-layer plastic cover can lower yields of many greenhouse crops.



(a) (b) (c) (d)

Figure 3–9
Hot water, root zone heating of propagation flats. (a) Biotherm tubing heating root zone of the plug tray. (b) Notice the probe (arrow) for regulating temperature. (c) The flexible hot water tubing is hooked into larger PVC pipes at set distances to assure more uniform heating. (d) Cuttings in propagation flats placed over white PVC hot water tubing; in milder climates, the ground hot water tubing may be all that is used to control root zone temperature and the air temperature of the propagation house.

(a) (b) (c) (d)

Figure 3–10
(a) Prop house with thermal and shade curtains (arrow) to reduce winter heating costs and reduce light irradiance and greenhouse cooling expenses during summer months. (b) Thermal screen for energy conservation, made of woven aluminized polyester fabric, covering for propagation house with 46 percent light transmission; (c and d) the fabric is placed on top of polyethylene propagation house the covered house.

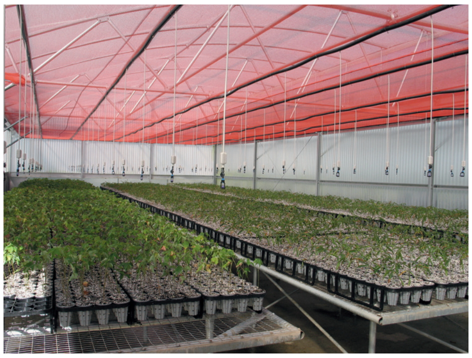
movable thermal curtains A device that reduces heat loss at night by creating a barrier between the crop and greenhouse roof and walls.

Another device that reduces heat loss dramatically is a **movable thermal curtain** (Fig. 3–10), which, at night, is placed between the crop and the propagation house roof and walls (119). Winter heating bills are reduced as much as 30 percent, since the peak of the propagation house is not heated (67). During summer, automated curtains also reduce heat stress on propagules and workers, and less energy is needed to run fans for cooling. Modified curtains can be used for light reduction during the day and **"black clothing"** for light exclusion during photoperiod manipulation of plants. Curtains range from 20 percent shade reduction to complete blackout curtains—ULS Obscura A + B (67). Curtain fibers are available in white, black, with aluminum coated fibers, and/or with strips of aluminum sewn in. Black shade cloth reduces light to the plants, but absorbs heat and emits heat back into the propagation house. Aluminum-coated curtain fabrics are good reflectors of light, but poor absorbers of heat (Fig. 3–10). Some curtain materials come with a top side for reflecting heat and reducing condensation and a bottom side for heat retention. Insulating the north wall reduces heat loss without appreciably lowering the available light. Heat reduction also occurs with red and blue shade cloth used for control of plant growth (Fig. 3–11).

black clothing A curtain that is drawn over plants to exclude light for manipulating photoperiod.

Greenhouses can be cooled mechanically in the summer by the use of large evaporative cooling units, as


(a)


(b)


(c)

Figure 3–11
(a and b) Propagation houses covered with red shade cloth for enhanced root initiation and development. The red netting increases the red, while reducing the blue and green spectra. (c) Shading seed propagation flats to reduce light irradiance and heat load.

pad and fan system
A system commonly used in greenhouse cooling to reduce the air temperature by raising the relative humidity and circulating air.

shown in Figure 3–12. The **"pad and fan" system,** in which a wet pad of material, such as special honeycombed cellulose, aluminum mesh, or plastic fiber, is installed at one side (or end) of a greenhouse with large exhaust fans at the other, has proved to be the best method of cooling greenhouses, especially in low-humidity climates (6). Fog can be used to cool greenhouses, but is more expensive than conventional pad and fan systems, and is inefficient in climates with high relative humidity (e.g., the Texas Gulf Coast).


(a)


(b)

Figure 3–12
Fully automated polycarbonate-covered greenhouse. (a) Air is pulled by exhaust fans (black arrow) to vent and cool. Components of both heating and cooling systems are electronically controlled via a weather monitoring station (white arrow) that feeds environmental inputs to computerized controls. (b) Cool cells (wettable pads) through which cooler, moist air is pulled across the propagation house by exhaust fans.

BOX 3.6 GETTING MORE IN DEPTH ON THE SUBJECT

ENVIRONMENTAL CONTROL EQUIPMENT

Environmental control equipment is available from such companies as Priva (www.priva.nl), Wadsworth Control Systems, Inc., (www.wadsworthcontrols.com), and HortiMaX USA Inc. (www.qcom-controls.com).

Greenhouses are often sprayed on the outside at the onset of warm spring weather with a thin layer of *whitewash* or a white cold-water paint. This coating reflects much of the heat from the sun, thus preventing excessively high temperatures in the greenhouse during summer. The whitewash is removed in the fall. Too heavy a coating of whitewash, however, can reduce the light irradiance to undesirably low levels. Aluminized polyester fabric coverings are used for reducing heat load and can be placed on top of polyethylene-covered propagation houses (Fig. 3–10).

Environmental Controls

Controls are needed for greenhouse heating and evaporative cooling systems. Although varying with the plant species, a minimum night temperature of 13 to 15.5°C (55 to 60°F) is common. Thermostats for evaporative cooling are generally set to start the fans at about 24°C (75°F). In the early days of greenhouse operation, light, temperature, and humidity were about the only environmental controls attempted. Spraying the greenhouse with whitewash in summer and opening and closing side and ridge vents with a crank to control temperatures, along with turning on steam valves at night to prevent freezing, constituted environmental control. Humidity was increased by spraying the walks and benches by hand at least once a day. Later, it was found that thermostats, operating solenoid valves, could activate electric motors to raise and lower vents, and to open and close steam and water valves, thus giving some degree of automatic control. Most environmental controllers of greenhouse environments are now analog or computerized systems.

Analog Environmental Controls Analog controls (i.e., Wadsworth Step 500) have evolved for controlling the greenhouse environment. They use proportioning thermostats or electronic sensors to gather temperature information. This information drives amplifiers and electronic logic (i.e., decision making) circuitry (55). Essentially, they combine functions of several thermostats into one unit (10). Analog controls cost more than thermostats, but are more versatile and offer better performance.

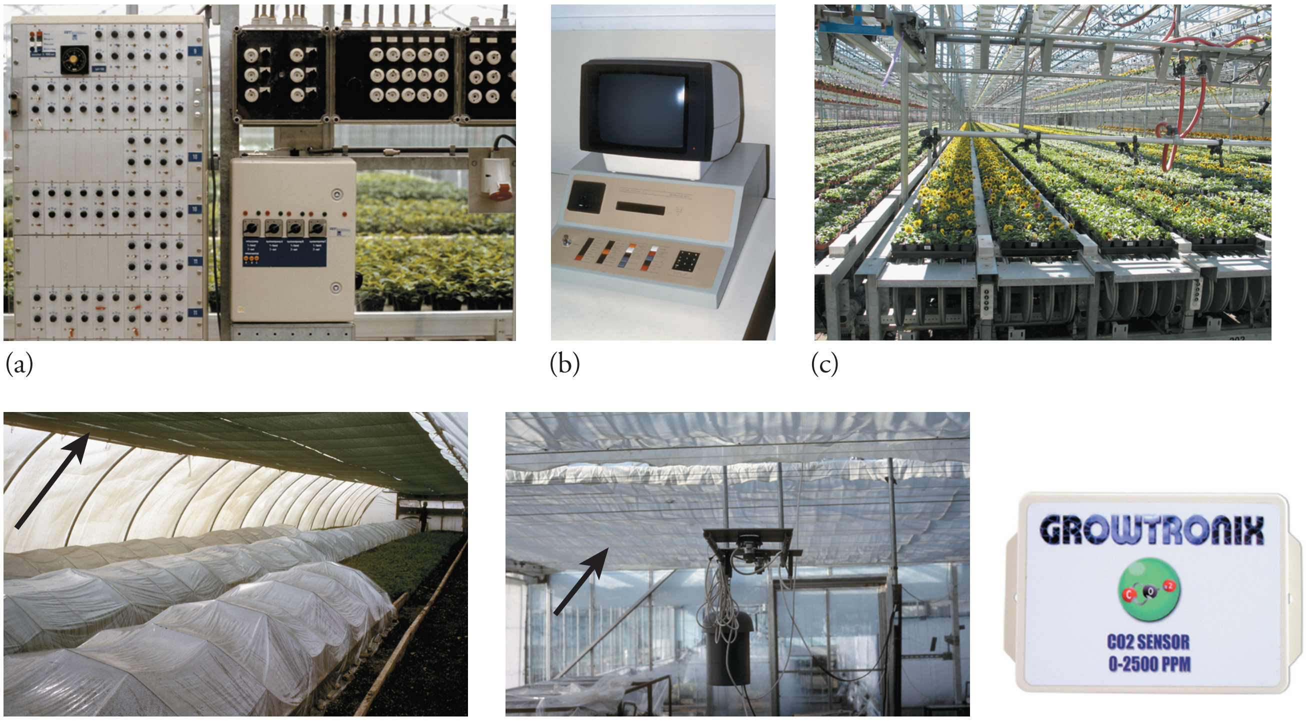
Computerized Environmental Controls The advent of computer technology (i.e., Wadsworth EnviroSTEP) has replaced the amplifiers and logic circuits of an analog control with a microprocessor "computer on a chip" (Figs. 3–13 and 3–14). Computer controls are quicker and more precise in combining information from a variety of sensors (temperature, relative humidity, light intensity, wind direction) to make complex judgments about how to control the propagation environment. Computers can be utilized as zone controllers or in more expensive integrated computer systems (10, 55).

Although more costly than thermostats or analogs, computer controls offer significant energy and labor savings and improved production efficiency in propagation. Not only can temperature, ventilation, and humidity be controlled, but many other factors, such as propagating bed temperatures, application of liquid fertilizers through the irrigation system, daylength lighting, light-intensity regulation with mechanically operated shade cloth (and thermal sheets or curtains), operation of a mist or fog system, and CO_2 enrichment—all can be varied for different times of the day and night and for different banks of propagation units (7, 47, 56, 124). Computers can be programmed so that alarms are triggered or propagators paged by phone if deviations from preset levels occur—such as a heating failure on a cold winter night or a mist system failure on cuttings on a hot summer day. Some of these operations are shown in Figures 3–12, 3–13, 3–14, and 3–15. Most importantly, the computer can provide data on all factors being controlled for review to determine if changes are needed. This makes it easier for the propagator to make management decisions based on factual information (42).

Greenhouse Covering Materials

Common greenhouse covering materials include (54, 103):

- Glass
- Flexible covering materials
- Rigid covering materials



(a) (b) (c)

(d) (e) (f)

Figure 3–13
(a and b) Computer-controlled environmental manipulation of propagation facilities including (c) a mechanized traveling mist boom for irrigating flats on moveable benches. (d and e) Automated shade material programmed to close along the top of the propagation house when preset radiant energy levels are reached; this system works well with contact polyethylene propagation systems for rooting cuttings. (f) Automated metering system for monitoring CO_2 injection in propagation house.

Glass Glass-covered greenhouses are expensive, but for a permanent long-term installation under low-light winter conditions, glass may be more satisfactory than the popular, low-cost polyethylene (poly)-covered houses. Due to economics and the revolution in greenhouse covering materials from polyethylene to polycarbonates, glass greenhouses are no longer dominant. Glass is still used, due in part to its superior light transmitting properties and less excessive relative humidity problems. Glass "breathes" (the glass laps between panes allow air to enter), whereas polyethylene, acrylic, and polycarbonate-structured sheet houses are airtight, which can result in excessive humidity and undesirable water drip on the plants if not properly controlled. This problem can be overcome, however, by maintaining adequate ventilation and heating. Some of the newer greenhouse covering materials are designed to channel condensation to gutters, avoiding water dripping onto plant foliage. Control of high relative humidity is a key cultural technique to manage plant pathogens, since water can both disseminate pathogens and encourage plant infection. See the section on cultural controls in propagation under integrated pest management, later in the chapter.

Flexible Covering Materials are Categorized as Follows

Polyethylene (Polythene, Poly). Over half of the greenhouse area in the United States is covered with low-cost **polyethylene (poly),** most with inflated double layers, giving good insulating properties. Poly is the most popular covering for propagation houses. Several types of plastic are available, but most propagators use either single- or double-layered polyethylene. Poly materials are lightweight and relatively inexpensive compared with glass. Their light weight also permits a less expensive supporting framework than is required for glass. Polyethylene has a relatively short life. It breaks down in sunlight and must be replaced after one or two years, generally in the fall in preparation for winter. The new polys, with ultraviolet (UV) inhibitors, can last three to four

polyethylene (poly) A plastic covering used to cover propagation greenhouses.

(a) (b) (c)

(d) (e)

Figure 3–14
Manipulating the propagation environment. (a) Greenhouse sensors that are connected to an analog or computer-controlled environmental system. (b) Analog-type controller. (c) High vapor pressure sodium lighting for propagating plants during low-light conditions. (d and e) Lighting to extend photoperiod, which encourages (e) Japanese maple cuttings to avoid dormancy.

years, but in the southern United States where UV levels are higher, poly deteriorates more quickly and propagation houses need to be recovered more frequently.

A thickness of 4 to 6 mils (1 mil = 0.001 in) is recommended. For better insulation and lowered winter heating costs, a double layer of UV-inhibited copolymer material is used with a 2.5-cm (1-in) air gap between layers, kept separated by air pressure from a small blower.

Single-layer polyethylene-covered greenhouses lose more heat at night or in winter than a glass-covered house since polyethylene allows passage of heat energy from the soil and plants inside the greenhouse much more readily than glass. There are some newer infrared reflective polys, which save fuel but have lower light penetration than regular poly. Glass traps most infrared radiation, whereas polyethylene is transparent to it. However, double layer poly-covered greenhouses retain more heat than glass because the houses are more airtight and less infrared radiation escapes.

Only materials especially prepared for greenhouse covering should be used. Many installations, especially in windy areas, use a supporting material, usually welded wire mesh, for the polyethylene film. Occasionally, other supporting materials, such as Saran cloth, are used.

Polyethylene transmits about 85 percent of the sun's light, which is low compared with glass, but it passes all wavelengths of light required for plant growth. A tough, white, opaque film consisting of a mixture of polyethylene and vinyl plastic is available.

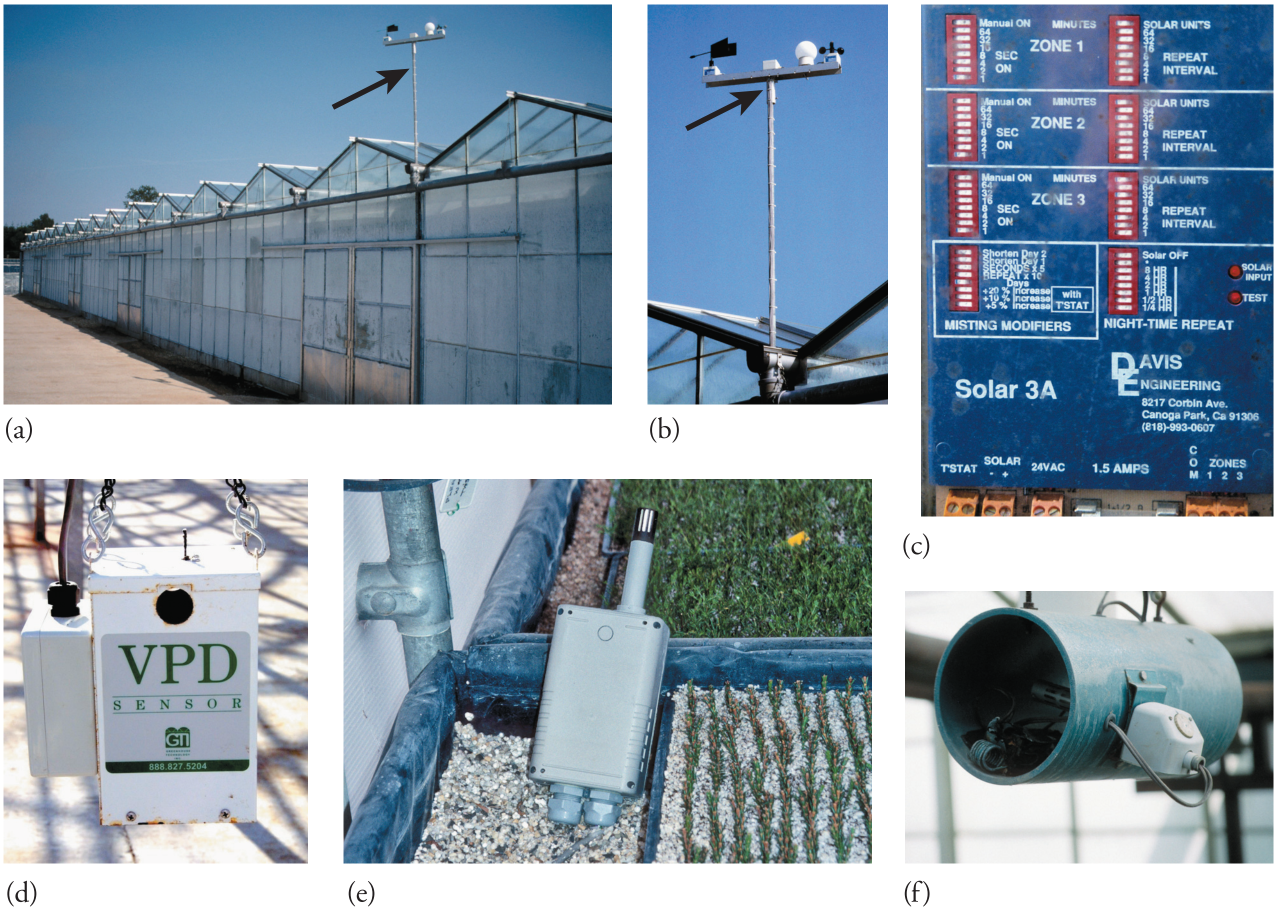


Figure 3–15
Environmental sensors for propagation. (a and b) A propagation house with a weather station for detecting light intensity, wind speed and direction, external temperature; this helps regulate temperature control and the fog propagation system. (c) Measurement of solar light allows for better mist control. (d, e, and f) Relative humidity sensors are needed to determine vapor pressure deficit (VPD) for critical fog propagation control.

This film stays more flexible under low winter temperatures than does clear polyethylene, but is more expensive. Because temperature fluctuates less under opaque film than under clear plastic, it is suitable for winter protection of field-bed or container-grown, liner plants (Fig. 3–16). Polyethylene permits the passage of oxygen and carbon dioxide, necessary for the growth processes of plants, while reducing the passage of water vapor.

For covering lath and shade structures, there are a number of satisfactory plastic materials prepared for the horticultural industry. Some commercially available materials include UV-treated cross-woven polyethylene and polypropylene fabric that resists ripping and tearing, and knitted high-density UV polyethylene shade cloth and Saran cloth that is strong and has greater longevity.

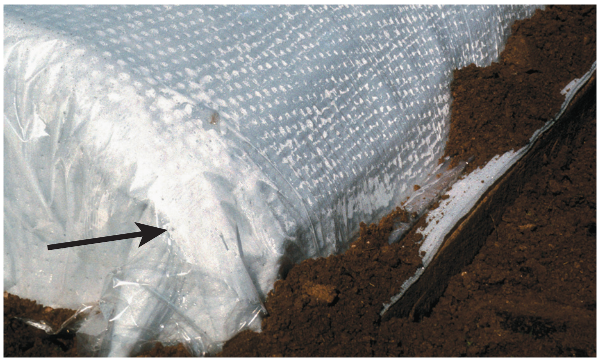
Rigid Covering (Structured Sheet) Materials Rigid Covering (Structured Sheet) Materials are Categorized as Follows

Acrylic (Plexiglass, Lucite, Exolite). Acrylic is highly weather resistant, does not yellow with age, has excellent light transmission properties, retains twice the heat of glass, and is very resistant to impact, but is brittle. It is somewhat more expensive and nearly as combustible as fiberglass. It is available in twin-wall construction which gives good insulation properties, and has a no-drip construction that channels condensation to run down to the gutters, rather than dripping on plants.

Polycarbonate (Polygal, Lexan, Cyroflex, Dynaglas). Polycarbonate is probably the most widely used structured sheet material today (55). Similar to acrylic in heat retention properties, it allows about 90 percent of

(a)

(b)



(c)

Figure 3–16
Low polyethylene tunnel or sun tunnel that is covered with polyethylene. (a) Sometimes a white poly material is used to avoid the higher temperature buildup and temperature fluctuation of clear poly. Propagation flats are placed on top of hot-water tubing or electric heating cables (b) Saran shade cloth can be used to cover the poly to reduce the heat load. (c) Winterization of sun tunnels can be done with white microfoam insulation covered with a clear poly or opaque poly (see arrow).

the light transmission of glass. Polycarbonate has high impact strength—about 200 times that of glass. It is lightweight, about one-sixth that of glass, making it easy to install. Polycarbonate's textured surface diffuses light and reduces condensation drip. It is available in twin-wall construction, which gives good insulation properties. Polycarbonate can be cut, sawn, drilled, or nailed, and is much more user-friendly than acrylic, which can shatter if nails or screws are driven into it. It is UV stabilized and will resist long outdoor exposure (some polycarbonates are guaranteed for ten years), but will eventually yellow with age (11, 90).

Fiberglass. Rigid panels, corrugated or flat, of polyester resin reinforced with fiberglass have been widely used for greenhouse construction. This material is strong, long-lasting, lightweight, and easily applied, and comes in a variety of dimensions (width, length, and thickness), but is not as permanent as glass. Only the clear material—especially made for greenhouses and in a thickness of 0.096 cm (0.038 in) or more and weighing 4 to 5 oz per square foot—should be used. New material transmits about 80 to 90 percent of the available light, but light transmission decreases over the years due to yellowing, which is a serious problem. Since fiberglass burns rapidly, an entire greenhouse may quickly be consumed by fire, so insurance costs can be higher. Fiberglass is more expensive than polyethylene, and is not as widely used as it once was.

The economics of using these greenhouse covering materials must be considered carefully before a decision is made. New materials are continually coming onto the market.

Closed-Case Propagation Systems

Hot Frames (Hotbeds) and Heated Sun Tunnels The **hot frame (hotbed)** is a small, low structure used for many of the same purposes as a propagation house. Traditionally, the hotbed is a large wooden box or frame with a sloping, tight-fitting lid made of window sash. Hotbeds can be used throughout the year, except in areas with severe winters where their use may be restricted to spring, summer, and fall. Another form of a hotbed is a **heated, low polyethylene tunnel or sun tunnel** that is made from hooped metal tubing or bent PVC pipe, which is covered with polyethylene (sometimes a white poly material is used to avoid the higher temperature buildup and temperature fluctuations of clear poly) (Fig. 3–16).

hot frames (hotbeds)
Propagation structures that are covered with poly and heated in the winter.

Traditionally, the size of the frame conforms to the size of the glass sash available—a standard size is 0.9 by 1.8 m (3 by 6 ft) (Fig. 3–17). If polyethylene is used as the covering, any convenient dimensions can be

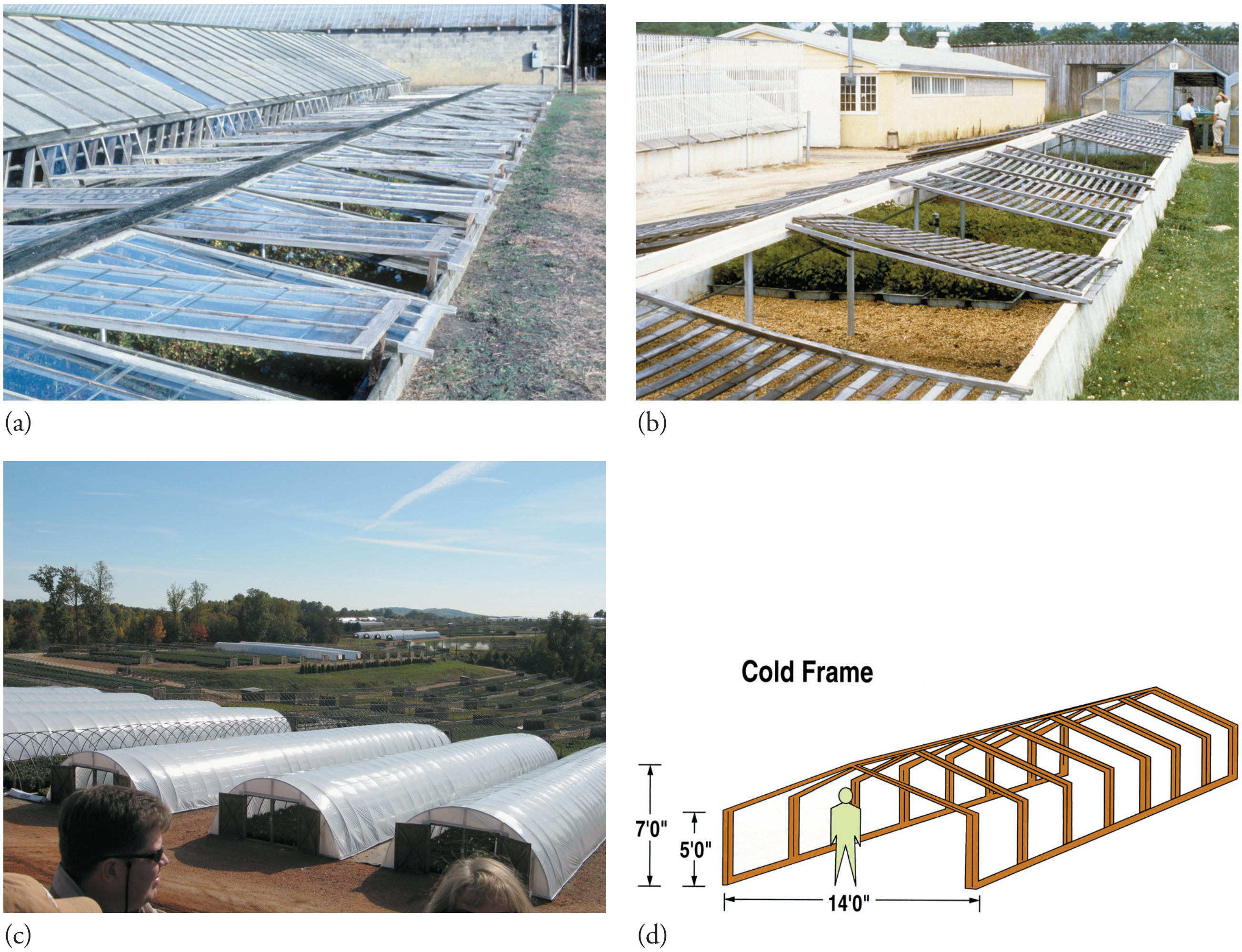


Figure 3–17
Traditional cold frames were used for propagating tender plants. Frames are opened after protection is no longer required. (a) Older commercial use of glass-covered cold frames in propagating ground cover plants by cuttings. (b) Wood sash used for liner production in a cold frame. Glass and lath coverings are rarely used due to the high labor costs in moving the heavy sash. Plastic coverings are more suitable. (c and d) Today a cold frame is most commonly a very low cost, budget, unheated poly-covered hoop or galvanized steel bow house.

used. The frame can be easily built with 3-cm (1-in) or 6-cm (2-in) lumber nailed to 4-by-4 corner posts set in the ground. Decay-resistant wood such as redwood, cypress, or cedar should be used, and preferably pressure-treated with wood preservatives, such as chromated copper arsenate (CCA). This compound retards decay for many years and does not give off fumes toxic to plants. Creosote must not be used on wood structures in which plants will be grown, since the fumes released, particularly on hot days, are toxic to plants.

Plastic or PVC tubing with recirculating hot water is quite satisfactory for providing bottom heat in hotbeds. The hotbed is filled with 10 to 15 cm (4 to 6 in) of a rooting or seed-germinating medium over the hot-water tubing. Alternatively, community propagation flats or flats with liner pots containing the medium can be used. These are placed directly on a thin layer of sand covering the hot-water tubing.

Seedlings can be started and leafy cuttings rooted in hotbeds early in the season. As in the greenhouse, close attention must be paid to shading and ventilation, as well as to temperature and humidity control. For small propagation operations, hotbed structures are suitable for producing many thousands of nursery plants without the higher construction expenditure for larger, walk-in propagation houses (60).

Cold Frames and Unheated Sun Tunnels A primary use of **cold frames** is conditioning or hardening

cold frames Propagation structures covered with poly, lath, or other covering material and which are not heated in the winter.

rooted cuttings or young seedlings (liners) preceding field, nursery-row, or container planting. Cold frames and unheated sun tunnels can be used for starting new plants in late spring, summer, or fall when no external supply of heat is necessary (129). Today, cold frames include not only low polyethylene-covered wood frames or unheated sun tunnels that people cannot walk within (Fig. 3–17), but also low-cost, poly-covered hoop houses (Fig. 3–17). The covered frames should fit tightly in order to retain heat and obtain high humidity. Cold frames should be placed in locations protected from winds, with the sash cover sloping down from north to south (south to north in the Southern Hemisphere).

Low-cost cold frame construction (Fig. 3–17) is the same as for hotbeds, except that no provision is made for supplying bottom heat. With older-style cold frames, sometimes a lath covering with open spaces between the lath boards is used to cover the cold frame. This does not prevent freezing temperatures from occurring, but does reduce high and low temperature fluctuations.

In these structures, only the heat of the sun, retained by the transparent or opaque white polyethylene coverings, is utilized. Close attention to ventilation, shading, watering, and winter protection is necessary for success with cold frames. When young, tender plants are first placed in a cold frame, the covers are generally kept tightly closed to maintain a high humidity, but as the plants become acclimated, the sash frames are gradually raised or the ends of the hoop house or sun tunnels opened to permit more ventilation and drier conditions.

The installation of a mist line or frequent irrigation of plants in a cold frame is essential to maintain humid conditions. During sunny days temperatures can build up to excessively high levels in closed frames unless ventilation and shading are provided. Spaced lath, Saran or poly shade cloth-covered frames, or reed mats are useful to lay over the sash to provide protection from the sun. In areas where extremely low temperatures occur, plants being overwintered in cold frames may require additional protective coverings.

Lathhouses Lathhouses or shade houses (Figs. 3–6 and 3–11) provide outdoor shade and protect container-grown plants from high summer temperatures and high light irradiance (50). They reduce moisture stress and decrease the water requirements of plants. Lathhouses have many uses in propagation, particularly in conjunction with the hardening-off and acclimation of liner plants prior to transplanting, and with maintenance of shade-requiring or tender plants. At times a lathhouse is used by nurseries simply to hold plants for sale. In mild climates, they are used for propagation, along with a mist facility, and can also be used as an overwintering structure for liner plants. Snow load can cause problems in higher latitude regions.

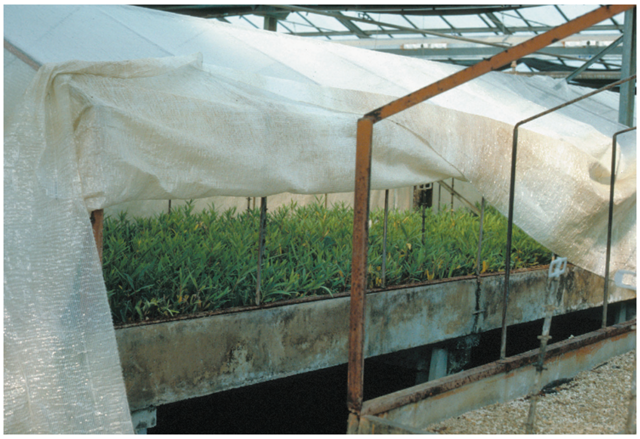
Lathhouse construction varies widely. Aluminum prefabricated lathhouses are available but may be more costly than wood structures. More commonly, pipe or wood supports are used, set in concrete with the necessary supporting cross-members. Today, most lathhouses are covered with high-density, woven, plastic materials, such as Saran, polypropylene fabric, and UV-treated polyethylene shade cloth, which come in varying shade percentages and colors. These materials are available in different densities, thus allowing lower irradiance of light, such as 50 percent sunlight, to the plants. They are lightweight and can be attached to heavy wire fastened to supporting posts. The shade cloth is resistant to ripping, and has an optimum life of 10 to 15 years, depending on climate and quality of material. For winterization in less temperate areas, producers will cover the shade cloth with polyethylene. Sometimes shade is provided by thin wood strips about 5 cm (2 in) wide, placed to give one-third to two-thirds cover, depending on the need. Both sides and the top are usually covered. Rolls of snow fencing attached to a supporting framework can be utilized for inexpensive construction.

Miscellaneous Closed-Case Systems There are a number of closed-case propagation systems that are used in the rooting of cuttings, acclimatization and rooting of tissue culture microcuttings, and propagation of seedlings. Besides the sun tunnels or cold frames previously described, closed-case propagation systems include nonmisted enclosures in glasshouses or polyhouses (shading, tent and contact polyethylene systems, wet tents, inverted glass jars).

Propagating Frames. Even in a greenhouse, humidity is not always high enough to permit satisfactory rooting of certain kinds of leafy cuttings. Enclosed frames covered with poly or glass may be necessary for successful rooting (see Figs. 3–18 and 10–36). There are many variations of such devices. Small ones were called Wardian cases in earlier days (see Fig. 1–3). Such enclosed frames are also useful for graft union formation of small potted nursery stock, since they retain high humidity.

Sometimes in cool summer climates (as far south as Virginia in the United States), when fall semi-hardwood cuttings are taken, a layer of very thin (1 or 2 mils) polyethylene laid directly on top of a bed of newly prepared leafy cuttings in a greenhouse or lathhouse will provide a sufficient increase in relative humidity to give good rooting. This is sometimes referred to as a **contact polyethylene system** (see Fig. 10–36). Good shade control to reduce light irradiance is essential for this system.


(a)


(b)


(c)

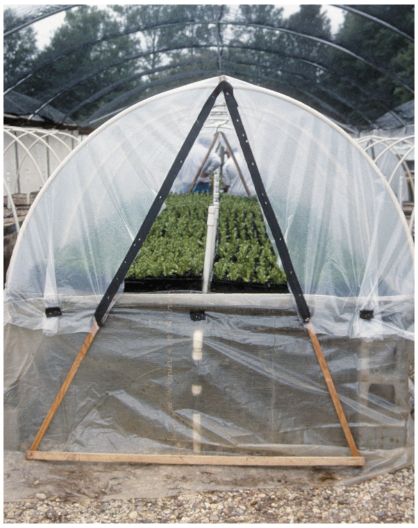

(d)

Figure 3–18
(a and b) Polyethylene-covered beds used in a greenhouse to maintain high humidity surrounding the cuttings during rooting. Propagation flats can be placed on beds or cuttings stuck directly into the mist beds and covered with poly. (c) Using shade (arrow) for light/temperature control. (d) Partially vented polycovered mist-bed under a quonset house for shade.

On a more limited scale, bell jars (large inverted glass jars) can be set over a container of unrooted cuttings or freshly grafted containerized plants to speed up graft union formation (see Fig. 12–49). Humidity is kept high in such devices, but some shading is necessary to control temperature.

In using all such structures, care is necessary to avoid the buildup of pathogenic organisms. The warm, humid conditions, combined with lack of air movement and relatively low light intensity, provide excellent conditions for the growth of various pathogenic fungi and bacteria. Cleanliness of all materials placed in such units is important; however, use of fungicides is sometimes necessary (see the section on **integrated pest management** later in the chapter).

Enclosed Poly Sweat Tent—Hydroponic System. An Australian producer of chrysanthemums uses a modified nutrient film technique (NFT) for growing greenhouse stock plants and propagating cuttings (58). Unrooted cuttings are stuck in Oasis root cubes and placed in mist propagation benches containing a reservoir of water, maintained with a float valve. The system is initially enclosed in a clear poly sweat tent. Once root initiation takes place, the mist is turned off and the poly tent lifted. Cuttings are then supplied with nutrient solution in the NFT system on the propagation bench and later transplanted with the roots intact and undisturbed in the root cube. Stock plants are also maintained in the NFT system and supported in root cubes, thus allowing more precise nutritional control and reduction in environmental stress to the stock plant.

CONTAINERS FOR PROPAGATING AND GROWING YOUNG LINER PLANTS

New types of containers for propagating and growing young liner plants are continually being developed, usually with a goal of reducing handling costs. Direct sticking of unrooted cuttings into small liner containers, as opposed to sticking into conventional propagation trays, saves a production step and later avoids root disturbance of cuttings, which can lead to transplant shock (Figs. 3–19, 3–20, and 3–21) (31).

Flats

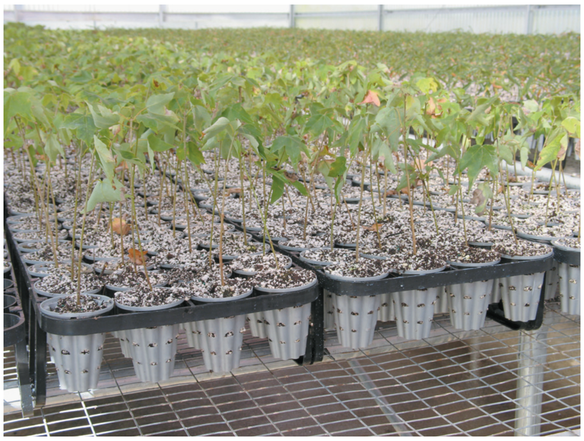
Flats are shallow plastic, Styrofoam, wooden, or metal trays, with drainage holes in the bottom. They are useful for germinating seeds or rooting cuttings, since they permit young plants to be moved easily. In the past, durable kinds of wood, such as cypress, cedar, or redwood, were preferred for flats. The most popular flats are made of rigid plastic (polyethylene, polystyrene) and come in all shapes and sizes. The 28 × 53 cm (11 × 21 in) *1020* plastic flats are the industry standard. The number of cells or compartments per tray may range from 1 cell for a community rooting flat or seed germination tray, to 18 or more cells for a rooted liner tray, to 100 to 400 cells for a seedling plug tray. Trays also can be fitted with removable sheet inserts containing the cells. Plastic flats will nest, and thus require relatively little storage space. The costs of producing plastic for flats and containers and for disposing of used plastic have led to increased plastic recycling programs in horticulture and biodegradable paper tube liner pots (Fig. 3–19).

Plastic Pots

Plastic containers, round and square, have numerous advantages: they are nonporous, reusable, lightweight, and use little storage space because they will nest. Some types are fragile, however, and require careful handling,

(a) (b) (c) (d)

Figure 3–19
(a and b) A paper pot system direct sticking (direct rooting) liner plants in paper tubes filled with peat-lite media. (b) Paper pot sleeve liner (arrow) inserted in plastic tray. (c) Rooted poinsettia in paper sleeve tube. (d) Plastic rooting tray with ribs (arrow) to reduce root circling of poinsettias during propagation and rooted liner development.



(a)

(b)

Figure 3–20
(a) Air-root pruning system for direct sticking (direct rooting) tree liners to minimize root circling, encourage more fibrous root development, and increase root surface area. (b) Direct rooting poinsettia cuttings in paper sleeves inserted in ribbed plastic liner pots.

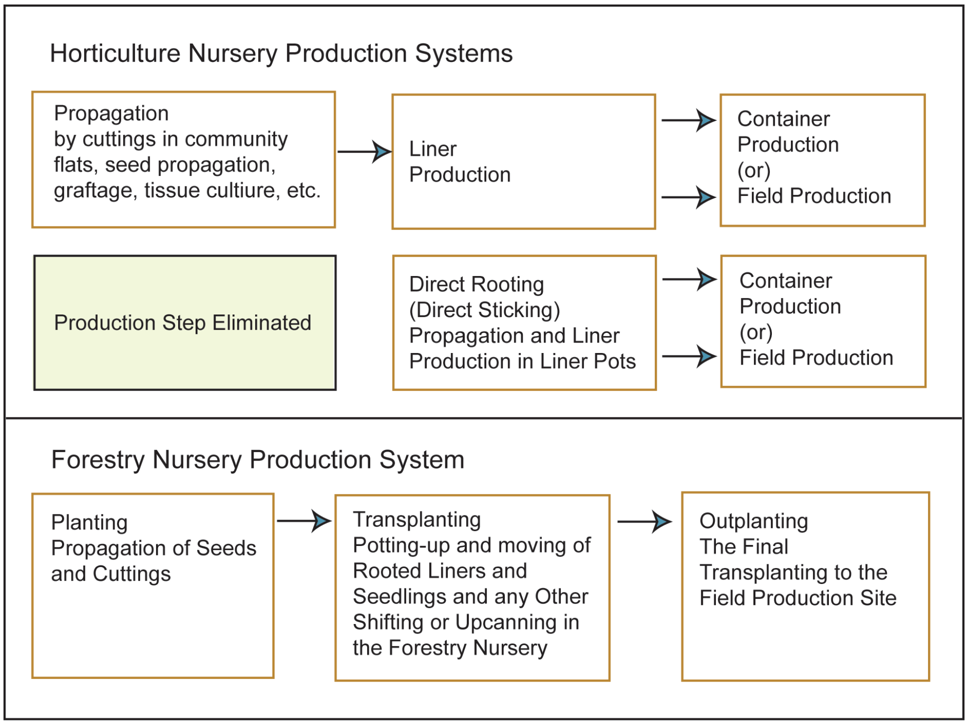
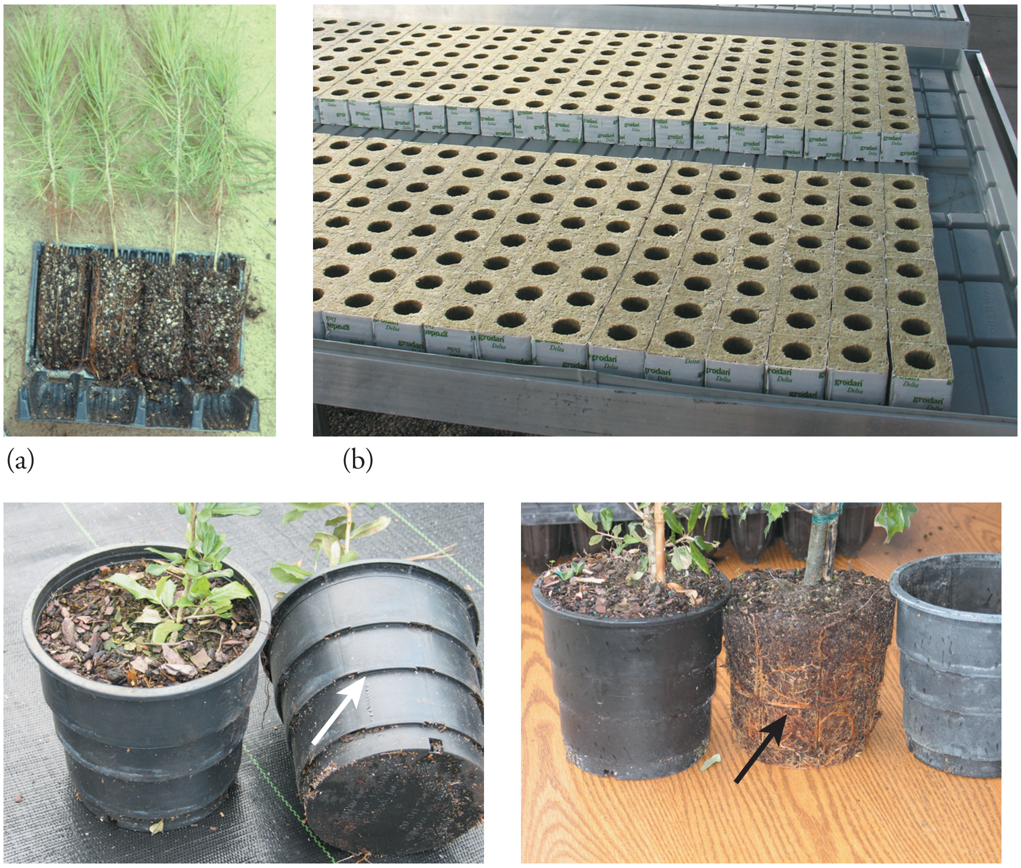


Figure 3–21
Flow diagram of a Horticulture Nursery Production System starting with propagation by rooted cuttings, seedlings, graftage, or tissue culture-produced plantlets—followed by transplanting into liner pots and final transplanting into larger containers or into nursery field production. Direct rooting (direct sticking) eliminates a production step, since both propagation and liner production occur in the same liner pot. A Forestry Nursery Production System of planting, transplanting, and outplanting is also described.



(a) (b) (c) (d)

Figure 3–22
(a) Plastic (Roottainer) container made of preformed, hinged sheets for propagating seedling liners. (b) synthetic fiber media (Rockwool) blocks for inserting seedling plugs and growing in greenhouse. (c and d) ridged containers for minimizing root circling.

although other types, made from polyethylene, are flexible and quite sturdy. Small liner pots for direct rooting of cuttings, seedling propagation, and tissue culture plantlet acclimatization and production have gained considerable popularity.

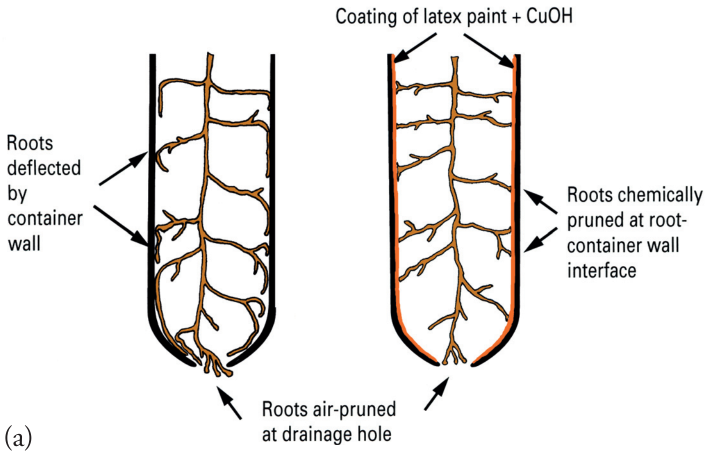
Many of these small containers have rib-like structures to redirect root growth and prevent girdling (Figs. 3–19, 3–20, and 3–22). In forestry seedling production, ribbed book or sleeve containers are used, which consist of two matched sections of molded plastic that fit together to form a row of rectangular cells (Fig. 3–22). The inner walls of small propagation containers and liner pots can also be treated with chemical root pruning agents, such as copper hydroxide ($CuOH_2$), which chemically prune liner roots at the root-wall interface (71). The chemically pruned lateral roots become suberized but will begin to grow again after transplanting, which results in a well-distributed root system that helps minimize transplant shock (Fig. 3–23) (71).

Plastic pots (and flats) cannot be steam sterilized, but some of the more common plant pathogens can be controlled by a hot water dip, 70°C (158°F), for 3 minutes followed by a rinse in a dilute bleach solution (i.e., Clorox, Purex, etc.). Ultraviolet light inhibitors are sometimes incorporated in the plastic resin to prevent UV degradation of plastic pots under full sun conditions (Fig. 3–24, page 75).

Fiber Pots

Containers of various sizes, round or square, are pressed into shape from peat plus wood fiber, with fertilizer added. Dry, they will keep indefinitely. Since these pots are biodegradable, they are set in the soil along with the plants. Peat pots find their best use where plants are to be held for a relatively short time and then put in a larger container or in the field. During outplanting in the field, any portion of the fiber pot transplanted above the surface of the soil will act like a wick and quickly dry out the transplant.

During production, small peat pots with plants growing in them eventually deteriorate because of constant moisture, and may fall apart when moved. On the other hand, unless the pots are kept moist, roots will fail to penetrate the walls of the pot and will grow into



(b)

(c)

Figure 3–23
Chemical root pruning involves treating the interior container wall with a growth-inhibiting chemical such as copper hydroxide. This causes the lateral roots to be chemically pruned at the container wall. A well-branched root system occurs, which enhances transplant establishment. (a) Schematic of nonpruned versus chemically pruned seedling container roots. (b) Copper hydroxide-treated container. (c) Copper hydroxide-treated *Acalpha hispida* (see arrow) without visible surface roots. Photo courtesy of M. Arnold.

an undesirable spiral pattern. Units of 6 or 12 square peat pots fastened together are available. When large numbers of plants are involved, using peat pots results in time and labor savings.

Paper Pots

Paper pots or paper tube pots are more popular with seed plug and cutting propagation of ornamentals, vegetable and forestry species. They allow for greater mechanization with pot-filling machines, automatic seeders, and wire benches that allow air pruning of the root system. Typically, paper pots consist of a series of interconnected paper cells arranged in a honeycomb pattern that can be separated before outplanting (71). An advantage of the paper pot system is that pots are biodegradable, and the seedling plug can be planted intact into a larger container or into the ground without disturbing the root system. Some papier-mâché

(a) (b)

Figure 3–24
(a) Colorful, labeled, rigid-plastic containers are used for growing and merchandising landscape and garden plants. Frequently, inhibitors are incorporated with the plastic resin to prevent ultraviolet breakdown of the containers under full sun conditions. (b) Flexible poly container bags are used for nursery production in Europe, England, and Australia, where petroleum-based products are more costly than in the United States.

pots (paper, wax, asphalt) come treated with copper hydroxide, which enhances root development and retards deterioration of the pot.

In Europe and the United States, paper tube pots with predictable degradation rates are produced by machine (39). The propagation medium is formed into a continuous cylinder and wrapped with a length of paper or cellulose skin that is glued and heat sealed (Fig. 3–19).

Peat, Fiber, Expanded Foam, and Rockwool Blocks

Blocks of solid material, sometimes with a prepunched hole (Fig. 3–22), have become popular as a germinating medium for seeds and as a rooting medium for cuttings, especially for such plants as chrysanthemums and poinsettias. Sometimes fertilizers are incorporated into the material. One type is made of highly compressed peat which, when water is added, swells to its usable size and is soft enough for the cutting or seed to be inserted. Such blocks become a part of the plant unit and are set in the soil along with the plant. These blocks replace not only the pot but also the propagating mix.

Synthetic rooting blocks (oasis, rockwool) are becoming more widely used in the nursery industry (and forestry industry for seed propagation), and are well adapted to automation (Fig. 3–22). Other advantages are their light weight, consistent quality, reproducibility, and clean condition. Watering must be carefully controlled to provide constant moisture, while maintaining adequate aeration.

Plastic Growing Containers for Post-Liner Production

Many millions of nursery plants are grown and marketed each year in 3.8-liter (1-gal) and—to a lesser extent—11-liter (3-gal), 19-liter (5-gal), and larger containers. They are tapered for nesting and have drainage holes. Heavy-wall, injection-molded plastic containers are used extensively in the United States. Machine planters have been developed utilizing containers in which rooted cuttings or seedlings can be transplanted as rapidly as 10,000 or more a day. See the horticulture and forestry nursery production flow diagrams (Fig. 3–21). Plants are easily removed from tapered containers by inverting and tapping. Some plastic containers are made of preformed, hinged plastic sheets that can be separated for easy removal of the liner (Fig. 3–22).

In areas with high summer temperatures, use of light-colored (white or silver) containers may improve root growth by reducing heat damage to the roots, which is often encountered in dark-colored containers that absorb considerable heat when exposed to the sun. However, light-colored containers show dirt marks (as opposed to black or dark green containers) and must be cleaned prior to shipping. More and more colorful, labeled containers are being used for growing and merchandising landscape and garden plants (Fig. 3–24). A pot-in-pot system, in which a containerized plant is inserted into a hole in the ground lined with a plastic sleeve pot, helps moderate both high and low rootball temperatures (Fig. 3–25).

Polyethylene Bags and Plant Rolls

Polyethylene bags are widely used in Europe, Australia, New Zealand, and in less developed countries in the tropics—but rarely in North America—for growing rooted cuttings or seedling liners to a salable size. They are considerably less expensive than rigid plastic containers and seem to be satisfactory (Fig. 3–24), but some types deteriorate rapidly. They are usually black, but some are black on the inside and light-colored on the outside. The lighter color reflects heat and lowers the root temperature. Polybags do not prohibit root spiraling or allow air pruning, which is a drawback to their use in propagation and liner production; however,

Figure 3–25
Alternatives to traditional field production. (a) In-ground fabric containers or grow bags. (b) The pot-in-pot (P&P) system with individual pot, drip irrigation. (c) Copper-treated wall of outside sleeve containers (arrow) to prevent root penetration from the inner pots. (d and e) P&P containers. (f) The roots of the inside containers are very susceptible to heat stress when they are removed from the field. Here they are wrapped with an insulating packing fabric for shipping.

(a) (c) (b)

Figure 3–26
(a) Redwood containers used for large nursery specimen tree production. (b) Wood containerized tree and heavy equipment required to lift it. (c) A large, 8- to 9-year-old specimen tree produced in a 183 cm (72-in) box, weighing in excess of 3700 kg (8100 lbs). The enormous weight of the rootball will require a crane for lifting at the landscape site. The box is easier for landscapers to handle than heavy-duty plastic container that would need to be cut up.

poly tubes are open-ended, which reduces girdling problems. After planting, they cannot be stacked as easily as the rigid containers for truck transportation—the polybags often break, and the root system of the plant is more easily damaged.

A low-cost method of propagating some easy-to-root species is with a polyethylene plant roll (see Fig. 10–58). The basal ends of the cuttings are inserted in damp peat moss or sphagnum and rolled into the doubled-over plastic sheeting. The roll of cuttings is then set upright in a humid location for rooting. Polyethylene starter pouches with an absorbent paper inserted in the pouch are used for germinating selected seed lots.

Wood Containers

Large cedar-wood containers or boxes are used for growing large specimen trees and shrubs to provide "instant" landscaping for the customer. Some of the specimen trees are 8 to 9 years old and weigh up to 3700 kg (8100 lbs). Heavy moving equipment is required for handling such large nursery stock (Fig. 3–26).

MANAGEMENT OF MEDIA AND NUTRITION IN PROPAGATION AND LINER PRODUCTION

Media and Mixes for Propagating and Growing Young Liner Plants

Various substrates and mixtures of materials are used for germinating seeds and rooting cuttings. For good results, the following characteristics of the medium are required (51):

- The **medium must be sufficiently firm and dense** to hold the cuttings or seeds in place during rooting or germination. Its volume must be fairly constant when either wet or dry; excessive shrinkage after drying is undesirable.
- It should be **highly decomposed and stable** (preferably with a 20C:1N ratio) to prevent N immobilization and excessive shrinkage during production.
- It must be **easy to wet** (not too hydrophobic) and retain enough moisture to reduce frequent watering.

- It must be **sufficiently porous** so that excess water drains away, permitting adequate penetration of oxygen to the roots—all containers produce a perched water table that creates a zone of saturated growing medium at the bottom of the container.
- It must be **free from pests:** weed seeds, nematodes, and various pathogens.
- It must have a **low salinity** level.
- It should be **capable of being steam-pasteurized or chemically treated** without harmful effects.
- It should have a **high cation exchange capacity (CEC)** for retention of nutrients that may be applied preincorporated and/or in a supplementary soluble and/or controlled-release fertilizer program.
- It should be of **consistent quality** from batch to batch, and reproducible.
- It should be readily **available,** and **economical.**

Propagation media used in horticulture and forestry consist of a mixture of organic and inorganic components that have different but complementary properties. The **organic component** generally includes peat, softwood and hardwood barks, or sphagnum moss. Sawdust and rice hulls should be avoided since they oxidize readily and compact easily, which decreases pore space and aeration, and they have a high C:N ratio, which can result in nutritional problems for the propagule. A **coarse mineral component** is used to improve drainage and aeration by increasing the proportion of large, air-filled pores. A variety of mineral components include sand (avoid fine particle sands), grit, pumice, scoria, expanded shale, perlite, vermiculite, polystyrene, clay granules, and rockwool.

There is no single, ideal mix. An appropriate propagation medium depends on the species, propagule type, season, and propagation system (i.e., with fog, a waterlogged medium is less of a problem than with mist); cost and availability of the medium components are other considerations. The following media components can be used in propagation systems.

Soil A mineral soil is composed of materials in the solid, liquid, and gaseous states. For satisfactory plant growth, these materials must exist in the proper proportions. The solid portion of a soil is comprised of both inorganic and organic components. The inorganic part consists of the residue from parent rock after decomposition, resulting from the chemical and physical process of weathering. Such inorganic components vary in size from gravel down to extremely minute colloidal particles of clay, the texture of the soil being determined by the relative proportions of these particle sizes. The coarser particles serve mainly as a supporting framework for the remainder of the soil, whereas the colloidal clay fractions of the soil serve as storehouses for nutrients that are released and absorbed by plants. The organic portion of the soil consists of both living and dead organisms. Insects, worms, fungi, bacteria, and plant roots generally constitute the living organic matter, whereas the remains of such animal and plant life in various stages of decay make up the dead organic material. The residue from such decay (termed **humus**) is largely colloidal and assists in holding water and plant nutrients.

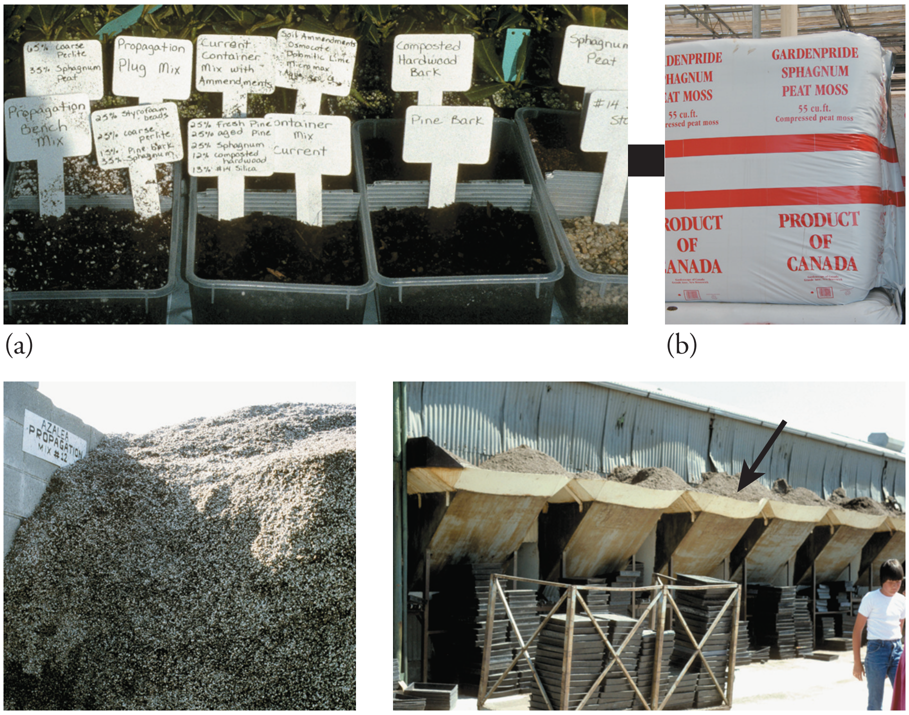
The liquid part of the soil, the soil solution, is made up of water that contains dissolved salts in various quantities, along with dissolved oxygen and carbon dioxide. Mineral elements, water, and some carbon dioxide enter the plant from the soil solution.

The gaseous portion of the soil is important to good plant growth. In poorly drained, waterlogged soils, water replaces the air, thus depriving plant roots as well as certain desirable aerobic microorganisms of the oxygen necessary for their existence.

The **texture** of a mineral soil depends upon the relative proportions of sand (0.05 to 2 mm particle diameter), silt (0.05 to 0.002 mm particle diameter), and clay (less than 0.002 mm particle diameter). In contrast to soil texture, which refers to the proportions of individual soil particles, **soil structure** refers to the arrangement of those particles in the entire soil mass. These individual soil grains are held together in aggregates of various sizes and shapes.

Propagation in commercial horticulture is generally done with flats, containers, and/or pot systems using ***"soilless" media.*** Some exceptions to this are field budding and grafting systems, stooling and layering systems, field propagation of hardwood cuttings without intermittent mist (see Fig. 10-2), direct seeding of crops, and utilizing outdoor seedbeds. With the greater reliance on containerized systems for propagation, mineral soils are either unsuitable or must be amended with other components to improve aeration and prevent the compaction that occurs with the structural changes of mineral soils in a container.

Sand Sand consists of small rock particles, 0.05 to 2.0 mm in diameter, formed as the result of the weathering of various rocks. The mineral composition of sand depends upon the type of rock. Quartz sand, consisting chiefly of a silica complex, is generally used for propagation purposes. Sand is the heaviest of all rooting media used, with a cubic foot of dry sand weighing about



(a) (b) (c) (d)

Figure 3–27
Propagation medium. (a) Various types of propagation media components and mixes. (b) Sphagnum peat moss—excellent quality, but expensive. (c) A specialized azalea propagation mix composed of peat, bark, and perlite. (d) Media in bins used to fill propagation & liner flats inside the propagation house.

45 kg (100 lb). Preferably, it should be fumigated or steam-pasteurized before use, as it may contain weed seeds and various harmful pathogens. Sand contains virtually no mineral nutrients and has no buffering capacity or cation exchange capacity (CEC). It is used mostly in combination with organic materials. Sand collected near the ocean (beach sand) may be too high in salts. Calcareous sand will raise media pH and should be tested prior to mixing with vinegar or a dilute acid.

Peat Peat consists of the remains of aquatic, marsh, bog, or swamp vegetation that has been preserved under water in a partially decomposed state. The lack of oxygen in the bog slows bacterial and chemical decomposition of the plant material. Composition of different peat deposits varies widely, depending upon the vegetation from which it originated, state of decomposition, mineral content, and degree of acidity (82).

There are three types of peat as classified by the United States Bureau of Mines: moss peat, reed sedge, and peat humus. *Moss peat* (usually referred to in the market as **peat** or **peat moss**) is the least decomposed of the three types and is derived from sphagnum or other mosses. It varies in color from light tan to dark brown. It has a high moisture-holding capacity (15 times its dry weight), has a high acidity (pH of 3.2 to 4.5), and contains a small amount of nitrogen (about 1 percent) but little or no phosphorus or potassium. This type of peat generally comes from Canada, Ireland, or Germany, although some is produced in the northern United States. *Peat moss is the most commonly used peat in horticulture, the coarse grade being the best* (Fig. 3–27).

When peat moss is to be used in mixes, it should be broken apart and moistened before being added to the mix. Continued addition of coarse organic materials such as peat moss or sphagnum moss to greenhouse media can initially cause a decrease in wettability. Water will not penetrate easily, and many of the peat particles will remain dry even after watering. There is no good method for preventing this nonwettability, although the repeated use of commercial wetting agents, such as Aqua-Gro, can improve water penetration (12). Peat is not a uniform product and can be a source of weed seed, insects, and disease inoculum. Peat moss is relatively expensive so it is used less in nursery propagation and production mixes. It is gradually being replaced by other components, such as pulverized or shredded bark. However, peat is still the main organic ingredient in propagation and greenhouse mixes.

Sphagnum Moss Peat Commercial sphagnum moss peat or sphagnum peat is the dehydrated young residue or living portions of acid-bog plants in the genus *Sphagnum,* such as *S. papillosum, S. capillaceum,* and *S. palustre.* It is the most desirable peat for horticultural purposes, but its high cost limits its commercial use. It is relatively pathogen-free, light in weight, and has a very high water-holding capacity, able to absorb 10 to

20 times its weight in water. This material is generally shredded, either mechanically or by hand, before it is used in a propagating or growing media. It contains small amounts of minerals, but plants grown in it for any length of time require added nutrients. Sphagnum moss has a pH of about 3.5 to 4.0. It may contain specific fungistatic substances, including a strain of *Streptomyces* bacteria, which can inhibit damping-off of seedlings (2, 63).

Vermiculite Vermiculite is a micaceous mineral that expands markedly when heated. Extensive deposits are found in Montana, North Carolina, and South Africa. Chemically, it is a hydrated magnesium-aluminum-iron silicate. When expanded, vermiculite is very light in weight [90 to 150 kg per cubic meter (6 to 10 lbs per cubic foot)], neutral in reaction with good buffering properties, and insoluble in water. It is able to absorb large quantities of water—40 to 54 liters per cubic meter (3 to 4 gal per cubic foot). Vermiculite has a relatively high cation-exchange capacity and, thus, can hold nutrients in reserve for later release. It contains magnesium and potassium, but supplementary amounts are needed from other fertilizer sources.

In crude vermiculite ore, the particles consist of many thin, separate layers with microscopic quantities of water trapped between them. When run through furnaces at temperatures near 1090°C (1994°F), the water turns to steam, popping the layers apart and forming small, porous, spongelike kernels. Heating to this temperature provides complete sterilization. Horticultural vermiculite is graded to four sizes: No. 1 has particles from 5 to 8 mm in diameter; No. 2, the regular horticultural grade, from 2 to 3 mm; No. 3, from 1 to 2 mm; No. 4, which is most useful as a seed-germinating medium, from 0.75 to 1 mm. Expanded vermiculite should not be compacted when wet, as pressing destroys its desirable porous structure. Do not use nonhorticultural (construction grade) vermiculite, as it is treated with chemicals toxic to plant tissues.

Perlite Perlite, a gray-white silicaceous material, is of volcanic origin, mined from lava flows. The crude ore is crushed and screened, then heated in furnaces to about 760°C (1400°F), at which temperature the small amount of moisture in the particles changes to steam, expanding the particles to small, spongelike kernels that are very light, weighing only 80 to 100 kg per cubic meter (5 to 6.5 lbs per cubic foot). The high processing temperature provides a sterile product. Usually, a particle size of 1.6 to 3.0 mm (1/16 to 1/8 in) in diameter is used in horticultural applications (Fig. 3–27). Perlite holds three to four times its weight of water. It is essentially neutral with a pH of 6.0 to 8.0 but with no buffering capacity. Unlike vermiculite, it has no cation exchange capacity and contains no mineral nutrients. Perlite presents some problems with fluoride-sensitive plants, but fluoride can be leached out by watering heavily. It is most useful in increasing aeration in a mix. Perlite, in combination with peat moss, is a very popular rooting medium for cuttings (85). Perlite dust is a respiratory irritant. Perlite should be moistened to minimize dust, and workers should use respirators.

Calcined Clay and Other Aggregates Stable aggregates can be produced when minerals such as clay, shales, and pulverized fuel ash are heated (calcined) at high temperatures. They have no fertilizer value, are porous, are resistant to breakdown, and absorb water. The main purpose of these materials is to change the physical characteristics of a propagation or liner potting mix. Examples of commercial materials made from clay include Leca, Terragreen, and Turfice. Haydite is a combination of clay and shale, while Hortag (used in the UK) is made from pulverized fuel ash (16). Clay-type kitty litter is also a calcined clay, but contains perfumes that are not desirable for propagation.

Pumice Chemically, pumice is mostly silicon dioxide and aluminum oxide, with small amounts of iron, calcium, magnesium, and sodium in the oxide form. It is of volcanic origin and is mined in several regions in the western United States. Pumice is screened to different-size grades, but is not heat-treated. It increases aeration and drainage in a propagation mix and can be used alone or mixed with peat moss.

Rockwool (Mineral Wool) This material is used as a rooting and growing medium in Europe, Australia, and the United States (Figs. 3–22 and 3–27). It is prepared from various rock sources, such as basalt rock, melted at a temperature of about 1600°C. As it cools, a binder is added, and it is spun into fibers and pressed into blocks. Horticultural rockwool is available in several forms—shredded, prills (pellets), slabs, blocks, cubes, or combined with peat moss as a mixture. Rockwool will hold a considerable amount of water, yet retains good oxygen levels. With the addition of fertilizers it can be used in place of the Peat-Lite mixes. Before switching from more traditional media mixes, it is best to initially conduct small-scale propagation trials with rockwool and other new media components as they become commercially available (51).

Shredded Bark Shredded or pulverized softwood bark from redwood, cedar, fir, pine, hemlock, or various hardwood bark species, such as oaks and maples, can be used as an organic component in propagation and growing mixes and are frequently substituted for peat moss at a lower cost (89, 91, 102, 112, 128). Before it is used as a growing medium, pine bark is hammer-milled into smaller component pieces, stockpiled in the open, and often composted by turning the piles and watering as needed. Fresh barks may contain materials toxic to plants, such as phenols, resins, terpenes, and tannins. Composting for 10 to 14 weeks before using reduces phenolic levels in bark and improves its wettability as media, and the higher bark pile temperatures help reduce insect and pathogen levels (16). Because of their moderate cost, light weight, and availability, barks are very popular and widely used in mixes for propagation and container-grown plants (Fig. 3–27). Wetting agents and gels increase available water content in pine bark and may play a greater role in helping propagators reduce irrigation frequency or the volume of water required during each irrigation (12).

Coconut Fiber/Coir Coconut fiber (coir) is an economical peat substitute that can be mixed with a mineral component as propagation media. It is derived from coconut husks.

Compost In some countries, compost is synonymous with container media for propagation and plant growth; however, we define *compost* (composting) as the product of biological decomposition of bulk organic wastes under controlled conditions, which takes place in piles or bins. The process occurs in three steps:

a. an initial stage lasting a few days in which decomposition of easily degradable soluble materials occurs;
b. a second stage lasting several months, during which high temperatures occur and cellulose compounds are broken down; and
c. a final stabilization stage when decomposition decreases, temperatures lower, and microorganisms recolonize the material.

Microorganisms include bacteria, fungi, and nematodes; larger organisms, such as millipedes, soil mites, beetles, springtails, earthworms, earwigs, slugs, and sowbugs, can often be found in compost piles in great numbers. Compost prepared largely from leaves may have a high soluble salt content, which will inhibit plant growth, but salinity can be lowered by leaching with water before use.

In the future, with dwindling landfill sites and environmental pressures to recycle organic scrapage materials, the use of composted yard wastes, chicken and cow manure, organic sludge from municipal sewage treatment plants, and so on will play a greater role as media components in the propagation and production of small liner plants. Many nurseries recycle culled, containerized plants and shred the plant and soil as compost or as a medium component to be mixed with fresh container medium. Composted sewage sludge not only provides organic matter, but nearly all the essential trace elements, and a large percentage of major elements needed by plants in a slowly available form (53). Mixes should always be analyzed for heavy metals and soluble salt levels. The usual recommended rate is that compost not comprise more than 30 percent of the volume of the mix (16).

Suggested Mixes—Media and Preplant Granular Fertilizers for Container Growing During Propagation and Liner Production

Following propagation, young seedlings, rooted cuttings, or acclimatized tissue culture plantlets (liners) are sometimes planted directly in the field but frequently are started in a blended, soilless mix in some type of container. Container growing of young seedlings and rooted cuttings has become an important alternative for field growers. In the southern and western United States, more than 80 percent of nursery plants are container produced (35). For this purpose, special growing mixes are needed (99, 128). It is sometimes more economical for a propagator to buy bags or bulk forms of premixed media. Typically, they are composed of a peat or peat-vermiculite, peat-perlite, hammer-milled and composted bark, rockwool, and other combinations. Preplant amendments in these mixes normally include dolomitic limestone, wetting agents (surfactants) to improve water retention and drainage of the peat or bark, starter fertilizers, trace elements, and sometimes gypsum and a pH buffer.

In preparing container mixes, the media should be screened for uniformity to eliminate excessively large particles. If the materials are very dry, they should be moistened slightly; this applies particularly to peat and bark, which, if mixed when dry, absorb moisture very slowly. In mixing, the various ingredients may be arranged in layers in a pile and turned with a shovel. A power-driven cement mixer, soil shredder, or front-end loader is used in large-scale operations. Most nurseries omit mineral soil from their mixes. The majority of container mixes for propagation and liner production use an organic component such as a bark or peat, which solely or in combination is mixed with mineral components such as sand, vermiculite, or pumice, depending on their availability and cost.

Preparation of the mixture should preferably take place at least a day prior to use. During the ensuing 24 hours, the moisture tends to become equalized throughout the mixture. The mixture should be just slightly moist at the time of use so that it does not crumble; on the other hand, it should not be sufficiently wet to form a ball when squeezed in the hand (44). With barks and other organic matter and supplementary components, particularly rice hulls and sugarcane begasse, it is necessary to compost the material for a period of months before using it as a container medium component.

Container mixes require fertilizer supplements and continued feeding of the plants until they become established in their permanent locations (132). For example, one successful mix for small seedlings, rooted cuttings, and bedding plants consists of one part each of shredded fir or hammer-milled pine bark, peat moss, perlite, and sand. To this mixture is added **preplant fertilizers**—gypsum, dolomitic limestone, microelements and sometimes controlled-release fertilizer. **Postplant fertilizers**—soluble forms of nitrogen, phosphorus, and potassium—are added later to the irrigation water (*fertigation*), or as a top dressing of controlled-release fertilizer, such as Osmocote or Nutricote.

preplant amendments/fertilizers Mineral nutrients that are applied to or incorporated in the propagation or container production media, prior to propagating propagules or transplanting liner plants into containers or into the field.

postplant amendments/fertilizers Mineral nutrients that are applied as a broadcast or liquid application during propagation or production of a containerized or field-grown plant.

In summary, nurseries have changed from loam-based growing media, as exemplified by the John Innes composts developed in England in the 1900s, to soilless mixes incorporating such materials as finely shredded bark, peat, sand, perlite, vermiculite, and pumice in varying proportions. The trend away from loam-based mixes is due to a lack of suitable uniform soils, the added costs of having to pasteurize soil mixes, and the costs of handling and shipping the heavier soils compared with lighter media materials. Much experimentation takes place in trying to develop other low-cost, readily available bulk material to be used as a component of growing mixes such as spent mushroom compost, papermill sludge (21, 26), composted sewage sludge (53), and other materials.

The Cornell Peat-Lite Mixes

The Cornell Peat-Lite mixes, like the earlier University of California (UC) potting mixes, are soilless media. First developed in the mid-1960s, they are used primarily for seed germination and for container growing of bedding plants, annuals, and flowering potted plants. The components are lightweight, uniform, readily available, and have chemical and physical characteristics suitable for the growth of plants. Excellent results have been obtained with these mixes. It may be desirable, however, to pasteurize the peat moss before use to eliminate any disease inoculum or other plant pests. Finely shredded bark is often substituted for the peat moss.

The term **peat-lite** refers to peat-based media containing perlite or vermiculite.

Peat-Lite Mix C (for germinating seeds): To Make 0.76 m^3 (1 cubic yard):

- 0.035 m^3 (1.2 ft^3) shredded German or Canadian sphagnum peat moss
- 0.035 m^3 (1.2 ft^3) horticultural grade vermiculite No. 4 (fine)
- 42 g (1.5 oz)—4 level tbsp ammonium nitrate
- 42 g (1.5 oz)—2 level tbsp superphosphate (20 percent), powdered
- 210 g (7.5 oz)—10 level tbsp finely ground dolomitic limestone

The materials should be mixed thoroughly, with special attention to wetting the peat moss during mixing. Adding a nonionic wetting agent, such as Aqua-Gro [(28 g (1 oz) per 23 liter (6 gal) of water)] usually aids in wetting the peat moss.

Many commercial ready-mixed preparations, based on the original Cornell peat-lite mixes, are available in bulk or bags and are widely used by propagators and producers. Some mixes are prefilled into cell packs, seed trays, or pots that are ready to be planted. Some soilless proprietary mixes are very sophisticated, containing peat moss, vermiculite, and perlite, plus a nutrient charge of nitrogen, potassium, phosphorus, dolomitic limestone, micronutrients, and a wetting agent with the pH adjusted to about 6.5.

Proprietary micronutrient materials, such as Esmigran, FTE 503, or Micromax, consisting of combinations of minor elements, are available for adding to growing media. Adding a controlled-release fertilizer such as Osmocote, MagAmp, Nutriform, Nutricote, or Polyon to the basic Peat-Lite mix is useful if the plants are to be grown in it for an extended period of time.

BOX 3.7 **GETTING MORE IN DEPTH ON THE SUBJECT**

SOME SUPPLIERS OF COMMERCIAL MIXES IN NORTH AMERICA

Sun Gro Horticulture (www.sungro.com)
Premier Horticulture (www.premierhort.com)
Scotts Professional Horticulture Solutions (www.scottspro.com)
Ball Horticultural Company (www.ballhort.com)

Managing Plant Nutrition with Postplant Fertilization During and After the Propagation Cycle

Developing an *efficient fertilizer program* for container plants for the 21st Century depends on (a) minimizing the loss of fertilizer from the production area and (b) increasing the amount of fertilizer utilized or taken up by the plant (133, 134). Suggested levels of *preincorporated* (*preplant*) granular fertilizers were discussed in the previous section on container media for propagation and small linear production. This section discusses some general fertilization practices for management of plant nutrition during **propagation and liner production** (Fig. 3–21). Both soluble and slow-release fertilizers are utilized.

Liquid Fertilizers For large-scale greenhouse and nursery operations, it is more practical to prepare a liquid concentrate and inject it into the regular watering or irrigating system by the use of a proportioner—**fertigation.** The most economical source of fertilizers to be applied through the irrigation water is from dealers who manufacture soluble liquid fertilizer for field crops. It is no longer recommended to use superphosphate in soilless mixes with outdoor container production because of the phosphorus leaching that occurs. Hence, more efficient, soluble forms of phosphorus are used, such as phosphoric acid or ammonium phosphate, in liquid feed programs. Potassium is typically applied as potassium chloride, or potassium nitrate, and nitrogen as Uran 30 (15 percent urea, 15 percent NH_4NO_3) or ammonium nitrate in the liquid concentrate.

An example of a liquid fertilizer system for production of containerized plants is the Virginia Tech System (VTS). With the VTS, all nutrients are supplied to the container by injecting liquid fertilizers into the irrigation water (131, 132). A 10N-$4P_2O_5$-$6K_2O$ analysis liquid fertilizer is applied five times per week, 1.3 cm (0.5 in) each irrigation at an application rate of 100 to 80 ppm N, 15 to 10 ppm P, and 50 to 40 ppm K. Sometimes higher nitrogen levels are applied (200–300 ppm N), depending on the time of the year, plant growth conditions, or plant species. It is critical to regularly monitor soluble salt levels of the medium prior to fertigation. Supplemental micronutrients are also applied in a liquid form but from separate tanks and with separate injectors to prevent fertilizer precipitation. It is best to monitor soluble salt levels of the irrigation water by measuring electrical conductivity (EC) with a conductivity meter; that is, to apply 100 ppm N, the injector is set so that the conductivity of the irrigation water—minus the conductivity of the water before the fertilizer was injected—reads 0.55 mS/cm (millisiemens per cm or dS per m are the same units of measure) (132–134).

Controlled-Release Fertilizers (CRF) Controlled-release fertilizers (CRF) provide nutrients to the plants gradually over a long period and reduce the possibility of injury from excessive applications (127). There has been a long-term trend of nurseries in the southern United States incorporating CRF in propagation, liner and production media, and spot-fertilizing via liquid fertilizer (fertigation) or top-dressing with CRF. CRFs are some of the most cost-effective and ecologically friendly ways to fertilize plants because fertilizer is applied directly to the pots. In contrast, overhead fertigation with rainbird sprinkler-type systems is only about 30 percent efficient, and greater fertilizer runoff occurs from the container production area. Examples of CRF include Osmocote, Phycote, Nutricote, and Polyon, and some are available with micronutrients incorporated in the pellets. As previously described, for both cutting and seed propagation, a low concentration of macro and micro CRF can be included in the propagation mix, so the newly formed roots can have nutrients available for absorption (37). This is particularly important with mist propagation where nutrients can be leached out from both the plant and the medium.

Two types of CRF include coated water-soluble pellets or granules and inorganic materials that are slowly soluble, while slow-release, organic fertilizer includes organic materials of low solubility that gradually decompose by biological breakdown or by chemical hydrolysis.

Examples of the resin-coated-type pellets are (a) Osmocote, whose release rate depends on the thickness of the coating, and (b) Nutricote (105), whose release rate depends on a release agent in the coating. After a period of time the fertilizer will have completely diffused out of the pellets (130). Another kind of controlled-release fertilizer is the sulfur-coated urea granules, consisting of urea coated with a sulfur-wax mixture so that the final product is made up of about 82 percent urea, 13 percent sulfur, 2 percent wax, 2 percent diatomaceous earth, and 1 percent clay conditioner.

An example of the slowly soluble, inorganic type CRF is MagAmp (magnesium ammonium phosphate), an inorganic material of low water solubility. Added to the soilless mix, it supplies nutrients slowly for up to 2 years. MagAmp may be incorporated into media prior to steam pasteurization without toxic effects. On the other hand, steam pasteurization and sand abrasion in the preparation of mixes containing resin-coated, slow-release fertilizers, such as Osmocote, can lead to premature breakdown of the pellets and high soluble salt toxicity.

An example of the slow-release, organic, low-solubility type is urea-formaldehyde (UF), which will supply nitrogen slowly over a long period of time. Another organic slow-release fertilizer is isobutylidene diurea (IBDU), which is a condensation product of urea and isobutylaldehyde, having 31 percent nitrogen.

Fertilizer Systems for Propagation Commercial propagators often apply moderate levels of controlled-release macro and micro elements to the propagation media—preincorporated into the media—prior to sticking cuttings and starting seed germination and seedling plug production. During propagation, supplemental fertilizer is added by top dressing (broadcasting) with controlled-release fertilizer or by injecting gradually increasing concentrations of liquid fertilizer (fertigation). These supplementary nutrients do not promote root initiation (30) in cuttings, but rather enhance root development after root primordia initiation has occurred. Hence, supplementary fertilization is generally delayed until cuttings have begun to root. Propagation turnover occurs more quickly and plant growth is maintained by producing rooted liners and plugs that are more nutritionally fit.

Some recommended levels of CRF for propagation are:

- 3.6 kg/m^3 (6 lb/yd^3) 18-6-12 Osmocote (or comparable product)
- 0.6 kg/m^3 (1 lb/yd^3) Micromax or other trace element mixtures—Perk, Esmigran, or FTE 503
- For unrooted cuttings, fast-germinating seeds, and tissue culture liners, CRF are preincorporated in the propagation media. For slower rooting or seed-germinating species, use Osmocote 153 g/m^2 (0.5 oz/ft^2).
- Nutricote and others are top-dressed on the media after rooting or seed germination starts to occur. Determining optimum levels of fertilization for propagation depends on the propagule system, and needs to be determined on a species basis (30).

Fertilizer Systems for Liner Production Soilless mixes must have fertilizers added (107, 132). Irrigation water and the container medium should be thoroughly analyzed for soluble salts, pH, and macro- and microelements before a fertility program can be established. It is always wise to conduct small trials before initiating large-scale fertility programs during propagation and liner production.

A satisfactory feeding program for growing liner plants is to combine a slowly available dry, granular fertilizer (preplant) in the original mix, with a (postplant) liquid fertilizer applied at frequent intervals during the growing season or with CRF added as top dressings, as needed (49).

Of the three major elements—nitrogen, phosphorus, and potassium—nitrogen has the most control on the amount of vegetative shoot growth. Phosphorus is very important, too, for root development, plant energy reactions, and photosynthesis. Potassium is important for plant water relations and enhanced drought resistance (40).

Nitrogen and potassium are usually supplied by CRF or fertigation—*100 to 80 ppm nitrogen* and *50 to 40 ppm potassium* are optional container medium levels when the Virginia Tech Extraction Method (VTEM) is used (134).

Negatively charged ions, such as phosphorus, leach from soilless media, so small amounts of phosphorus must be added to the media frequently. Past research indicates that *15 to 10 ppm phosphorus* should be maintained in container medium as determined by the saturated paste or VTEM (131, 132). Phosphorus from superphosphate leaches rapidly; so in order to maintain 10 ppm in the medium, CRF is used or small amounts of phosphorus in soluble form are applied.

Calcium and magnesium are supplied as a preplant amendment in dolomitic limestone and may naturally be supplied by irrigation water. Limestone is primarily added to adjust the pH of the media. It is important to have the irrigation water checked to determine the level of dolomitic limestone needed, if any. VTEM levels of

40 ppm calcium and *20 ppm magnesium* in the container medium are adequate.

MANAGEMENT OF MICROCLIMATIC CONDITIONS IN PROPAGATION AND LINER PRODUCTION

Water

Quality (Salinity) of Irrigation Water Good water quality is essential for propagating quality plants (78). The salt tolerance of unrooted cuttings, germinating seeds, and tissue culture explants is much lower than that of established plants, which can be grown under minor irrigation salinity by modifying cultural conditions. **Water quality** for propagation is considered good when the electrical conductivity (EC) reading is 0.75 mS (millisiemens) per cm or dS (decisiemens) per m (less than 525 ppm total soluble salts in ppm), and the sodium absorption ratio (SAR) is 5. Except for the most salt-tolerant plants, irrigation water with total soluble salts in excess of 1,400 ppm (approximately 2 mS/cm) (ocean water averages about 35,000 ppm) would be unsuitable for propagation. Salts are combinations of such cations as sodium, calcium, and magnesium with such anions as sulfate, chloride, and bicarbonate. Water containing a high proportion of sodium to calcium and magnesium can adversely affect the physical properties and water-absorption rates of propagation media and should not be used for irrigation purposes. It is prudent to have nursery irrigation water tested at least twice a year by a reputable laboratory that is prepared to evaluate all the elements in the water affecting plant growth. Most producers regularly monitor EC and pH of their irrigation water and container mix with inexpensive instruments. Some producers test and monitor their own container media nutrients, whereas plant leaf tissue is generally sent off to plant laboratories for nutrient analysis.

water quality The amount of soluble salts (**salinity**) in irrigation water, which is measured with an electrical conductivity meter.

Although not itself detrimental to plant tissue, so-called hard water contains relatively high amounts of calcium and magnesium (as bicarbonates and sulfates) and can be a problem in mist-propagating units or in evaporative water cooling systems because deposits build up wherever evaporation occurs, which reduces the photosynthetic levels of cuttings, seedlings, and tissue culture plantlets. When *hard* water is run through a water softener, some types of exchange units replace the calcium and magnesium in the water with sodium ions. Misting and irrigating with such *soft,* high-sodium water can injure plant tissue.

A better, but more costly, method of improving water quality is using **deionization (DI).** Water passes over an absorptive cation resin to filter positively charged ions such as calcium and other ions in exchange for hydrogen. For further deionization, the water is passed through a second anion resin to filter out negatively charged ions such as carbonates, sulfates, and chlorides in exchange for hydroxyl (OH) ions.

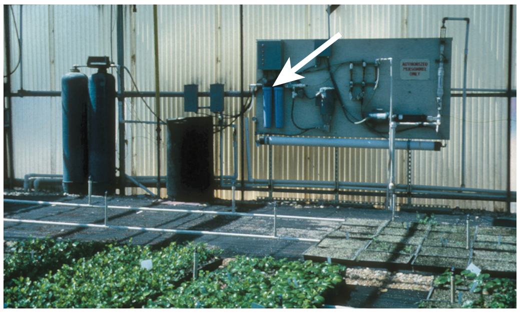
Boron salts are not removed by deionization units, and, if present in water in excess of 1 ppm, they can cause plant injury. There is no satisfactory method for removing excess boron from water. The best solution is to acquire another water source and to use customized non-boron-blended fertilizers.

Another good, but expensive, method for improving water quality is **reverse osmosis (RO)** (Fig. 3–28), a process in which pressure applied to irrigation water forces it through a semipermeable membrane from a more concentrated solution to a less concentrated solution, eliminating unwanted salts from an otherwise good water source. There are combination RO/DI units, but they are cost-prohibitive for most propagation systems.

Municipal treatment of water supplies with chlorine (0.1 to 0.6 ppm) is not sufficiently high to cause plant injury. However, the addition of fluoride to water supplies at 1 ppm can cause leaf damage to a few tropical foliage plant species.

BOX 3.8 GETTING MORE IN DEPTH ON THE SUBJECT
MEASURING SALINITY

Salinity levels from irrigation water, and from water extracts of growing media (saturation-extract method) can be measured by electrical conductivity (EC) using a Solubridge. Various portable meters for testing salinity, as well as soil and water testing kits, are available through commercial greenhouse supply companies.


(a)


(b)


(c)

Figure 3–28
Good water quality is imperative for propagation. (a) A reverse osmosis system is shown for removing salts in commercial propagation. (b and c) Deionizing columns for removing salts.

When the water source is a pond, well, lake, or river, contamination by weed seeds, mosses, or algae can be a problem. Chemical contamination from drainage into the water source from herbicides applied to adjoining fields or from excess fertilizers on crop fields can also damage nursery plants. Recycled water, which is discussed in the section "Best Management Practices (BMP) (see page 98)," is used in nursery and greenhouse production, and is being evaluated for general propagation in some nurseries.

The pH of Irrigation Water and Substrate Media The pH is a measure of the concentration of hydrogen ions and can affect the rooting of cuttings, germination of

BOX 3.9 **GETTING MORE IN DEPTH ON THE SUBJECT**

TREATING RECYCLED IRRIGATION WATER

Nurseries using **recycled irrigation water** (Fig. 3–29) should treat the water before use. A good procedure is to:

- Initially utilize aquatic plants in runoff catchment ponds to reduce pollutants and sediments reentering the recycling system (113, 133).
- Add chlorine or bromine to suppress algae and plant pathogens as water is pumped from the catchment pond.
- Use strainers to remove large debris, then run the water through sand or mechanical filters with automatic back flushing to remove coarse particles and weed seed.
- Consider running the water through an activated charcoal tank to remove soluble herbicides and other residual chemicals.
- If the water has a high salt content, it can be improved by the use of deionization or reverse osmosis, but the processes are very expensive.
- Water can be treated with ultraviolet irradiation to reduce pathogens. Generally, all precipitate down to at least 20 μm is filtered out in order for UV light to be effective.
- Recycled water is acidified (to lower the pH, if necessary) and repumped into holding ponds with plastic liners and weed-free perimeters.
- Fresh well water is pumped into the holding pond and mixed with the recycled water. This allows for pumping from wells during the night to meet daily irrigation needs and dilutes soluble salts of recycled water.
- This water can then be used for field watering of container nursery plants and slow-release fertilizer incorporated into containers or soluble fertilizer injected into the irrigation system.

Figure 3–29
Systems for capturing, treating, and recycling irrigation water in commercial nurseries. (a and b) Irrigation water either drains into or is (c) pumped into a holding pond. (d) Irrigation water is treated with chlorine (sodium hypochlorite solution is one of the safest forms) as it is pumped from the holding pond into the irrigation lines system lines. (e) Filtration tanks for removing weed seed and particulate-suspended matter down to 20 mm (this is important if irrigation water is to be treated with ultraviolet light); some nurseries use tanks of activated charcoal to trap soluble herbicides and other undesirable chemicals. (f) Ultraviolet treatment of irrigation water with a UVS Ultra Pure model 5000. Scoresby, Victoria, Australia. (g) Bromination of water; some nurseries will inject acid at this point to lower water pH, if needed. (h) Monitoring water leaving the water treatment facility for pH and soluble salts or electrical conductivity (EC).

seeds, and micropropagation of explants. Liner production is also affected by pH influence on nutrient availability and activity of beneficial microorganisms in the container medium. A pH range of 5.5 to 7.0 is best for the growth of most plants (7.0 is neutral—below this level is acid and above is basic or alkaline). Nurseries may control carbonate problems by injecting sulfuric or phosphoric acid into the irrigation water supplies. Softwood bark and peat-based container mixes are acid and will lower irrigation water pH. Dolomitic limestone raises soil pH and is the primary source of Ca and Mg in many propagation and liner mixes. While pH is important, alkalinity has a greater impact on water quality (133).

Water-Humidity Control

Good water management is important to limiting plant stress. Care must be exercised to avoid overmisting and overirrigation, because too much water can be just as stressful as too little water. Root rots and damping-off organisms are favored by standing water and poor media drainage conditions.

Maintaining proper atmospheric humidity in the propagation house beds is important because low humidity can increase transpiration and subject unrooted cuttings and seedlings to water stress. Adequate humidity allows optimum growth, whereas extreme humidity promotes fungal pathogen, moss, and liverwort pests. Air always contains some water vapor, but at any given temperature it can hold only a finite amount. When the physical limit is reached, the air is **saturated,** and when it is exceeded, **condensation** occurs (72). The unique physical properties of water affect the propagation environment. When water is converted from a liquid to a gas (water vapor), a large amount of thermal energy (540 cal/g) is required. The cooling effect of mist irrigation results as heat is absorbed and the increased relative humidity minimizes plant transpiration. A heavy mist, which condenses and forms droplets of water, should be avoided because it leaches foliage of nutrients, saturates propagation media, and can promote disease problems.

Current systems used to control water loss of plant leaves (74) are:

1. **Enclosure Systems:** outdoor propagation under low tunnels or cold frames, or nonmisted enclosures in a glasshouse or polyhouse (shading, tent and contact polyethylene systems, wet tents).
2. **Intermittent Mist:** open and enclosed mist systems.
3. **Fogging Systems**

The effect of these systems on propagation environmental conditions and water relations of the propagule is discussed in greater detail in Chapter 9.

Temperature Control

As indicated in earlier sections, temperature is modified by environmental controls in the propagation structure and the type of propagation system that is used (see Chapter 9 for greater details). There is no environmental factor more critical than optimal temperature control for propagation. Optimal seed germination, rooting of cuttings, development of tissue culture plantlets, graft union formation, and specialized structure development are all temperature-driven plant responses. Hot air convection, infrared radiation, and hot water distribution systems are the three most viable ways to heat plants (Figs. 3–2 and 3–9). Of the three, hot water is the most flexible and commonly used system in propagation houses (98). It allows efficient root zone heating in the form of bottom heat. Some examples include Biotherm tubing and Delta tubes, which are used to maintain optimum propagation temperatures. A mist system accelerates root development of cuttings under high light irradiance, by evaporative cooling, which reduces the heat load on plant foliage. In fog systems, the fog particles remain suspended and reduce the light intensity, while a zero-transpiration environment is maintained, without the overwetting (condensation) that can occur with mist. Since only minimal condensation occurs, leaf and media temperatures are warmer with fog than mist. In liner production, DIF systems (cooler days and warmer night temperature) produce more compact plants. This works well for seedling plugs, bedding plants, and greenhouse crops under controlled environmental conditions (55).

Light Manipulation

The importance of light manipulation in propagation (irradiance, photoperiod, quality) was discussed earlier in the chapter and is covered in greater detail in later chapters on seed and cutting propagation, micropropagation, and specialized structure development and propagation. Light quality (which is commercially manipulated through greenhouse spectral filters, greenhouse coverings, and varying supplementary light sources) plays an important role in seed germination, and shoot development in macro- and micropropagation (Fig. 3–11). Photoperiod can be manipulated to delay bud dormancy and extend accelerated plant growth. Photoperiod can be utilized not only to enhance root initiation, but also to increase carbohydrate reserves of deciduous, rooted cuttings (liners) for better winter survival and subsequent vigorous spring growth (Fig. 3–14) (79).

Supplemental Photosynthetic Lighting in the Propagation House Plant growth in the winter in propagation houses can be slow due to the lack of sufficient light for photosynthesis, especially in the higher latitudes (19). This is due to several reasons:

- Low number of daily light hours
- Low angle of the sun, resulting in more of the earth's atmosphere that the sun's rays must penetrate
- Many cloudy and overcast days in the winter
- Shading by the greenhouse structure itself and dirt accumulating on the poly or glass or other covering materials

To overcome the problem of low natural winter light and reduced plant growth, supplemental light can be used over the plants (Fig. 3–14). The best light source for greenhouse lighting is high-pressure sodium vapor lamps. Most of the radiation from these lamps is in the red and yellow wavelengths and is very deficient in blue. However, when used in conjunction with the natural daylight radiation, these lamps are quite satisfactory.

The high-pressure sodium vapor lamps emit more photosynthetically active radiation (PAR) for each input watt of electricity than any other lamp that is commercially available. Sodium vapor lamps are long-lasting and degrade very slowly. They emit a considerable amount of heat that can be a benefit in the greenhouse in winter. They use a smaller fixture than fluorescent lamps, thus avoiding the substantial shading effect from the fluorescent lamp fixture itself. The installation should provide a minimum of about 65 μmol m^2 s^{-1} or 13 W/m^2 PAR at the plant level with a 16-hour photoperiod. For large greenhouses, the services of a lighting consultant should be used in designing the installation.

In the future, expect to see greater use of light-emitting diodes (LED) (86) with spectral qualities based on propagation needs under controlled environmental agriculture (CEA). The LED has no filament, just a microchip, and is extremely energy-efficient.

Photosynthetic lighting with high intensity discharge lights (HID) in more overcast climates has greatly expanded the production window for cuttings and seed propagation. Supplementary lighting is an important component in accelerated growth techniques (AGT) in propagating plants (Fig. 3–30).

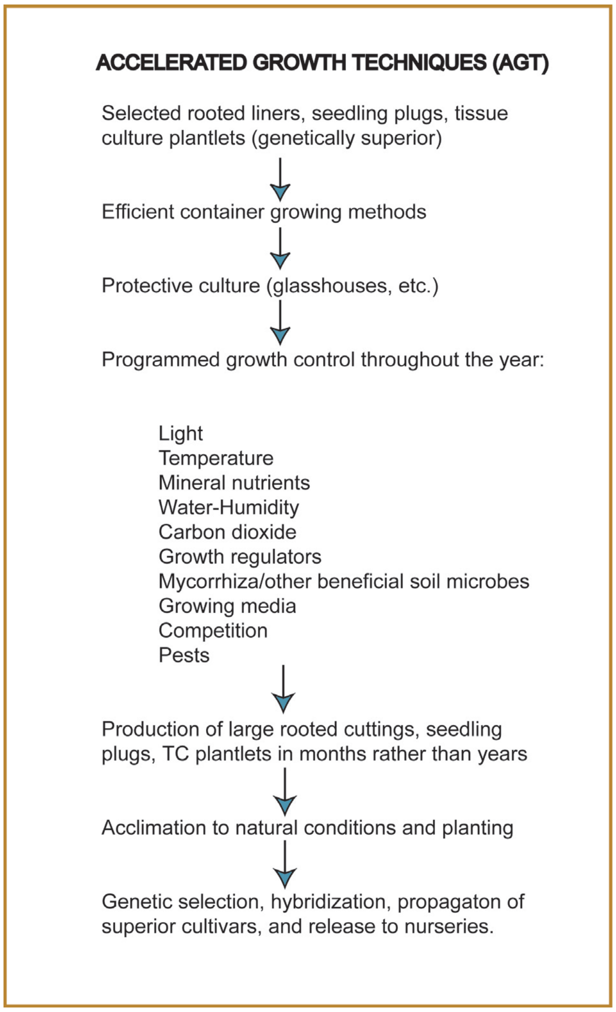


Figure 3–30
Components of accelerated growth techniques used in speeding up vegetative and seed propagation in the production of marketable liners.

Carbon Dioxide (CO_2) Enrichment in the Propagation House

Carbon dioxide is one of the required ingredients for the basic photosynthetic process that accounts for the dry-weight materials produced by the plant (59, 87, 94):

$$6H_2O + 6CO_2 + \text{Light Energy/Chlorophyll} : C_6H_{12}O_6 + 6O_2$$

Ambient carbon dioxide (CO_2) in the atmosphere is around 380 ppm. Sometimes the concentration in winter in closed greenhouses may drop to 200 ppm, or lower, during the sunlight hours, owing to its use by plants (94). Under adequate light and temperature, but when low CO_2 concentration limits photosynthesis, a supplementary increase in CO_2 concentration 1,000 to 2,400 ppm can result in a 200 percent increase in photosynthesis. To take full advantage of this potential increase in dry-weight production, plant spacing must avoid shading of overcrowded leaves. When supplementary CO_2 is used during periods of sunny weather, the temperature in the greenhouse should be kept relatively high. Adding CO_2 at night is of no value. However, CO_2 generators can be turned on before dawn to increase photosynthesis early in the day. A tightly closed greenhouse is necessary to be able to increase the ambient CO_2.

Sources of CO_2 for greenhouses are either burners using kerosene, propane, or natural gas, or liquid CO_2. Liquid CO_2 is expensive but almost risk free. Kerosene burners must use high-quality, low-sulfur kerosene or SO_2 pollution can occur. With propane or natural gas, incomplete combustion is possible—by-products include carbon monoxide (dangerous to humans) and ethylene (harmful to plants). The flames should be a solid blue color. Monitoring of the CO_2 level in the greenhouse is very important. Accurate, inexpensive sensors are available and should be used (Fig. 3–13). With the newer computer technology, sensors in different parts of the greenhouse can give excellent control of the CO_2 levels. Excessively high levels of CO_2 in the greenhouse (over 5,000 ppm) can be dangerous to humans.

New tissue culture systems are utilizing high CO_2 enrichment and high light levels for *autotrophic micropropagation* (65). The plantlets are cultured without sugar in the culture medium as an energy and carbon source, and are stimulated by enriched atmospheric CO_2 and elevated light irradiance to photosynthesize and become autotrophic. The CO_2 is supplied either directly to the tissue culture vessel or indirectly via increased ambient CO_2 to permeable culture vessels. Autotrophic micropropagation improves plantlet growth and development, simplifies procedures, reduces contamination, and lowers production costs (see Chapter 18).

Accelerated Growth Techniques (AGT)

The forestry industry developed accelerated growth systems to speed up the production of liners from cutting and seed propagation. Woody perennial plants undergo cyclic (episodic) growth, and many tree species experience dormancy. Liners are grown in protective culture facilities where photoperiod is extended and water, temperature, carbon dioxide, nutrition, mycorrhizal fungi, and growing media are optimized for each woody species at different growth phases (Fig. 3–30).

This concept is also being used in propagation of horticultural crops where supplementary lighting with high-pressure sodium vapor lamps and injection of CO_2 gas into mist water are used to enhance seed germination, plug development, acclimation of tissue culture plantlets, and rooting of cuttings. The promotive effects of AGT on rooting of *Ilex aquifolium* (holly) cuttings has been attributed, in part, to enhanced photosynthesis.

Modeling in Plant Propagation Closely linked to AGT is the modeling of propagation environments to determine optimal light, temperature, water, CO_2, and nutritional regimes (125, 126). Computer technology allows the propagator to monitor and program the propagation environment and adjust environmental conditions as needed through automated environmental control systems (see Figs. 3–13, 3–14, 3–15, 10–42, and 10–43).

BIOTIC FACTORS—PATHOGEN AND PEST MANAGEMENT IN PLANT PROPAGATION

Pathogen and pest management begins *prior to propagation* with the proper manipulation of stock plants or the container plants from which the propagules are harvested, as well as with management of propagation beds and media preparation. If pathogens and pests are not checked during propagation, an inferior plant is produced and later production phases for finishing and selling the crop will be delayed, causing profit losses.

Pests are broadly defined as all biological organisms (bacteria, viruses, viroids, phytoplasma, fungi, insects, mites, nematodes, weeds, parasitic higher plants, birds, and mammals) that interfere with plant production (57). *Insect pests,* such as aphids, mealy bugs, thrips, white flies, and fire ants, actively seek out the plant host by migrating (flying, walking). When an infection can be spread from plant to plant, it is referred to as an infectious disease. *Infectious plant diseases* are caused by different pathogens *(infectious agents),* including pathogenic fungi, bacteria, viruses, viroids, and phytoplasma. Specific pathogens may infect only certain plant species or cultivars, or specific organs or tissue, which varies with the stage of development of the plant.

The pathogenic fungi most likely to cause disease development during propagation are species of *Pythium, Phytophthora, Fusarium, Cylindrocladium, Thielaviopsis, Sclerotinia, Rhizoctonia,* and *Botrytis* (27). These are all soil-borne or aerial organisms (*Botrytis*) that infect plant roots, stems, crowns, or foliage. The so-called damping-off commonly encountered in seedbeds is caused by soil fungi, such as species of *Pythium, Phytophthora, Rhizoctonia,* and *Fusarium.* Suppressing pathogens in propagation water is critical—*Phytophthora, Pythium,* and *Rhizoctonia* are readily disseminated in surface water.

Conversely, intermittent mist can wash off germinating fungal spores. Mist inhibits the spore germination of powdery mildew (*Sphaerotheca pannosa*) on leaves of cuttings, and it may be that other disease organisms are held in check in the same manner. However, mist propagation is highly conducive to diseases such as aerial *Rhizoctonia* blight, *Cylindrocladium,* bacterial soft rots, and so on.

A goal in propagation is to keep stock plants and propagules as clean and pest-free as possible and to suppress pathogenic fungi, viruses, nematodes, and weed seed from the propagation media. Optimum pest management depends on a thorough knowledge of the pest life cycle, as well as environmental conditions, cultural practices, and minimizing host plant stress—the rooting of a cutting and germination of a seed are vulnerable periods of plant growth. A stressed propagule is much more susceptible to pest problems. The management of pests through integrated pest management (IPM) is discussed in this section.

Preventive Measures

Cultivar Resistance Avoid producing crops that are susceptible to certain diseases and pests. A susceptible crop means more time, chemicals, and money spent to control the problem. In addition, the problem is passed on from the propagator to the consumer (3). By choosing a resistant cultivar, efforts are concentrated on propagating and producing the plant, rather than trying to control the pest (i.e., propagate disease-resistant crab apple cultivars, rather than disease susceptible *Malus* cultivars such as 'Hopa' and 'Mary Potter'). In the southern United States, Helleri hollies (*Ilex* 'Helleri') are plagued by southern red mites, root-knot nematodes, and black root rot—so why propagate them when other holly cultivars are more resistant (3)?

Scouting System All propagators should practice pest scouting. Early detection provides more effective pest and pathogen control with less reliance on pesticides. Propagation houses should be scouted on a regular basis and all propagation employees trained to recognize and report disease and insect pests. Workers are the ones in daily contact with plants and are an invaluable resource for early detection. Some large nurseries have detailed pest management programs with crews supervised by trained plant pathologists and entomologists (23). Such programs involve the proactive prevention of plant diseases and the avoidance of insects, mites, and weed problems. Serological test kits—ELISA (enzyme-linked immunosorbent assays)—are commercially available to propagators for the early detection of certain pathogens and viruses (88, 95). The user-friendly Alert Diagnostic Kits can rapidly identify the damping-off organisms—*Pythium, Rhizoctonia, Phytophthora,* and *Botrytis* (2). (Keeping viruses in check is considered in Chapter 16.)

Integrated Pest Management in Plant Propagation

Integrated Pest Management (IPM) is the most efficient, most economical, most environmentally safe system for managing pests in propagation and liner production systems. The components of IPM are divided into three management areas:

- Chemical
- Biological
- Cultural

Total elimination of a pest is not always feasible—nor is it biologically desirable if the process is environmentally damaging or leads to new, more resistant pests and eliminates beneficial fungi and insects. In the production of clean stock plants and propagules, pest-free plants may be a requirement, but this should be accomplished by using a variety of pest management methods without an overdependence on just one method (i.e., solely using chemical control). **Pest control** differs from **pest management** in that an individual pest control technique is used in isolation to eliminate a pest and *all* pest-related damage (57). Conversely, IPM uses as many *management* (control) methods as possible in a systematic program of suppressing pests (not necessarily annihilating) to a commercially acceptable level, which is a more ecologically sound system.

Chemical Control in IPM Chemical control methods in IPM include the use of:

- Fumigation
- Fungicides
- Insecticides

IPM does not imply that no chemicals are used in the control of pests and pathogens. Rather, better-targeted control with less chemical usage occurs because of the integration of additional biological and cultural management measures (109). IPM in propagation means that actions must be thoughtfully considered and carried out in ways that will ensure favorable economic, ecological, and sociological consequences (52, 93).

In the treatment of seeds, bulbs, corms, tubers, and roots, pesticides are sometime used in combination with cultural techniques, such as hot water soaks [43 to 57°C (110 to 135°F)]. The hot water temperature and duration is dependent on the species and propagule type being treated. For many ornamental plants, to control decay and damping-off, seeds are treated with fungicidal slurries or dusts of thiram, zineb, and so on. Seeds of California poppy, and *Strelitzia* (bird of paradise) are given hot water soaks to control pathogenic fungi, while *Delphinium* (larkspur) and *Digitalis* (foxglove) seeds are given a hot water soak and then dusted with thiram to control anthracnose. Bulbs and corms of many species are treated for nematodes and pathogenic fungi with hot water soaks and/or chemical treatment.

When using pesticides, it is important that propagators follow the **Worker Protection Standard (WPS)** rules and regulations to reduce pesticide-related illnesses and injuries (45). The WPS can complicate many jobs in propagation. Scheduling has become more critical so pesticide restricted entry intervals **(REI)** do not interfere with normal propagation assignments of workers. The United States Environmental Protection Agency (EPA) has a monthly updated bulletin that details WPS implementation information on reentry rules and times; see their web site (www.epa.gov/pesticides).

Fumigation with Chemicals Chemical fumigation kills organisms in the propagating mixes without disrupting the physical and chemical characteristics of the mixes, to the extent occurring with heat treatments. (In all cases, recommendations on pesticide labels must be followed to conform to permitted usages.) The mixes should be moist (between 40 and 80 percent of field capacity) and at temperatures of 18 to 24°C (65 to 75°F) for satisfactory results. Before using the mixture and after chemical fumigation, allow a waiting period of 2 days to 2 weeks, depending on the material, for dissipation of the fumes. A problem with chemically sterile media is that there are no competing microorganisms to limit the rapid recolonization of fungi and bacterium, which may create media aeration and pest problems.

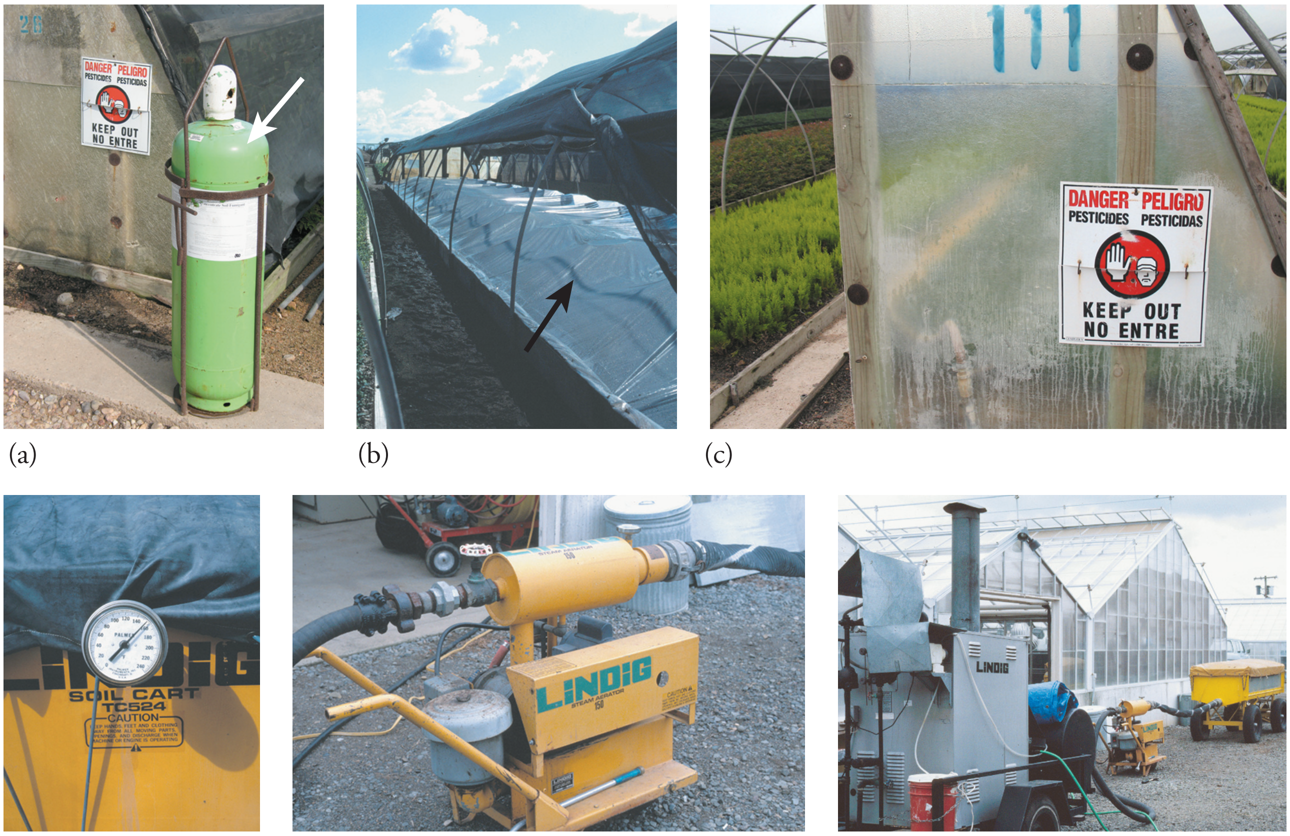
Methyl Bromide (MB). MB is a highly effective fumigant for propagation. It is odorless, very volatile, and quite **toxic to animals and humans.** Because it contributes to the reduction of the earth's ozone layer, developing countries are limiting the use of MB with a complete phase out in 2015. The U.S. EPA is currently revising the reregistration of methyl bromide. The USDA has a special web site on MB alternatives, including methyl iodide and metam sodium (18), for agriculture (http://www.ars.usda.gov/is/np/mba/mebrhp.htm). It should be mixed with other materials and applied only by those trained in its use. Most nematodes, insects, weed seeds, and fungi are killed by methyl bromide. Methyl bromide is most often used by injecting the material from pressurized containers into an open vessel placed under a plastic sheet that covers the soil to be treated (Fig. 3–31). The cover is sealed around the edges with soil and should be kept in place for 48 hours. Penetration is very good and its effect extends to a depth of about 30 cm (12 in).

Methyl Bromide and Chloropicrin Mixtures. Proprietary materials are available that contain both methyl bromide and chloropicrin. Such combinations are more effective than either material alone in controlling weeds, insects, nematodes, and soil-borne pathogens. The

BOX 3.10 **GETTING MORE IN DEPTH ON THE SUBJECT**

IPM IN THE CULTURAL CONTROL OF APHIDS

An example of IPM is the **cultural control of aphids** in propagation by installing *microscreening* that covers vents and doorways of a propagation house, thereby reducing the movement of insects and the need for insecticides (48). Early detection of winged aphids with *yellow sticky cards* that are hung in the propagation house can alert personnel to monitor plants near cards for the presence of wingless females. The option to use **biological control** is possible with an efficient scouting system that detects controllable, low aphid levels. A beneficial midge, *Aphidoletes aphidimyza,* has been used to biologically control aphid colonies. If the aphid colony is small, other *biorational products* can be used such as insecticidal soap (M-Pede), horticultural oils (UltraFine SunSpray spray oil), *botanical insecticides* such as neem (Azatin and Margosan-O), and natural pyrethrums. *Insect growth regulators* such as kinoprene (Enstar II) and methoprene give safe, effective control of immature aphids. For large populations of aphids that were not detected early enough, **chemical control** with traditional pesticides are sometimes used, such as diazinon, bendiocarb, methiocarb, acephate; or the synthetic pyrethroids, such as fluvalinate (Mavrik), bifenthrin (Talstar), and fenpropathrin (Tame) (48).



(a) (b) (c)

(d) (e) (f)

Figure 3–31
Chemical and heat treatment of propagation mixes. (a) Methyl bromide (MB) being applied to propagation medium. (b) Methyl bromide is injected into media covered with poly. (c) Methyl bromide is extremely toxic; during soil treatment it is important to use warning signs and restrict the movement of personnel. (d, e, and f) Heat pasteurization with aerated steam.

addition of chloropicrin (tear gas) to methyl bromide was primarily so that humans could detect gas leaks and evacuate before being poisoned by methyl bromide. Aeration for 10 to 14 days is required following applications of methyl bromide-chloropicrin mixtures.

Fungicidal Soil Drenches. Fungicidal soil drenches can be applied to the container media in which young plants are growing or are to be grown to suppress growth of many soil-borne fungi. These materials may be applied either to media or to the plants. Preferably, a wetting agent should be added to the chemicals before application. It is very important when using such chemicals to read and follow the manufacturer's directions and prepare dilutions carefully, and to try the chemicals on a limited number of plants before going to large-scale applications. As with insect pests, pathogens can build up resistance to fungicides, so it is important to rotate fungicides and use mixtures with good residual action (63).

BOX 3.11 **GETTING MORE IN DEPTH ON THE SUBJECT**
MINOR-USE CHEMICALS

Chemicals used in propagation and horticulture are considered **minor use,** as opposed to pesticides used for large commodity crops such as cotton, soybean, corn, and others. The cost for chemical companies to develop new or to reregister specialty or minor-use chemicals is often prohibitive. Hence, more than 1,000 minor uses of agricultural chemicals are currently at risk, and another 2,600 newly sought minor uses may never come to fruition because of the 1988 Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) (38) (see http://www.epa.gov/oecaagct/lfra.html).

Examples of fungicidal drench materials are Quintozene (PCNB, Terraclor), which controls *Rhizoctonia, Sclerotina,* and *Sclerotium.* Etridiazole (Terrazole, Truban) are incorporated into the propagating medium, which suppresses the water molds *Pythium* and *Phytophthora.* Banrot is a broad-spectrum fungicide that suppresses the damping-off organisms of *Pythium, Phytophthora,* and *Rhizoctonia,* as well as *Fusarium* and *Thielaviopsis.* Subdue and Heritage are some of the systemic fungicides used in propagation for control of root rots and foliar pathogens (27).

Propagators are adapting IPM systems—utilizing disease-free propagules, clean propagation media, disinfesting propagation facilities and incorporating beneficial rhizosphere organisms such as mycorrhiza; hence fungicidal sprays are applied only as needed and not as weekly preventive sprays (32). Some propagators dip the bottom 5 cm (2 in) of cuttings into Zerotol (hydrogen dioxide) to disinfect cuttings of potential pathogens; cuttings are then quick-dipped into auxin solutions for rooting (100).

Insecticidal Sprays and Drenches. An example of insecticidal spray and drench usage is in the control of fire ants, which are a major pest in the southern United States. The USDA implemented the Imported Fire Ant Quarantine and Imported Fire Ant Free Nursery program in 1958 to prevent the spread of fire ants, which infest twelve southern and western states and Puerto Rico. The ants are spread easily by accidentally shipping them with nursery stock and small liner plants. The ants do not directly harm plants and propagules (they will tend plants with aphids, and harvest the honeydew of the aphids from the plants' leaves)—but they do damage land and livestock, have killed people, and are a nuisance to propagation workers and the public. For short-term, small-container crops, such as liners, producers will drench plant containers with Dursban, Talstar 10WP, and Diazinon (in certain states). For propagation mixes and large-container crops, producers use soil-incorporated granular insecticide, such as Talstar and Dursban (22). Chemical baits are also effective for long-term fire ant control, but are slower acting than spray/drench applications; see the fire ant web site for the latest recommendations (http://fireant.tamu.edu).

Biological Control in IPM Biological control in IPM includes:

- Predator insects and mites
- Beneficial nematodes
- Beneficial fungi and bacteria

More and more insect pests and pathogens are being managed by biological methods. This is due in part to increased mite and insect resistance to pesticides, the fact that biological control can be cheaper and more effective than chemical control (i.e., two-spotted mite is effectively controlled by the Chilean predatory mite), increasing concern for environmental issues (contamination of groundwater, etc.), and worker safety (i.e., reentry times of workers after pesticide application, etc.). In the United States, there is the Association of Natural Biocontrol Producers (ANBP; www.anbp.org) for the production and utilization of beneficial insects and organisms.

In propagation, the bacterium *Bacillus thuringiensis* (BT) infects and controls most caterpillars and fungal gnat larvae but has little effect on other insects or the environment. Strains of this naturally occurring bacterium have been formulated into the biological control insecticides Dipel, Thuricide, Bactospeine, and so on.

Biofungicides are preventive, rather than curative, and must be applied or incorporated before disease onset to work properly. For example, the beneficial fungus *Trichoderma virens* (Soil-Gard) comes in an easy-to-apply granular form that is added to the propagation media. It has been cleared by the EPA for biological control of *Rhizoctonia colani* and *Pythium ultimum,* which are two of the principal pathogens causing damping-off diseases (31). Mycostop, a strain of *Streptomyces* bacteria isolated from Finnish peat, is used in propagation as a drench; dip for transplants, seeds, and cuttings; or as a foliar spray. It controls *Fusarium, Alternaria,* and *Phomopsis,* and suppresses *Botrytis, Pythium,* and *Phytophthora* (2, 63).

As higher plants have evolved, so have beneficial below-ground organisms interacting with the plant root system (the plant **rhizosphere**). Examples of this include symbiotic nitrogen-fixing bacteria, which are important for leguminous plants, and selected nematodes that control fungal gnats (i.e., X-Gnat from Biosys). The nematodes come in water-dispersible granules, are applied with overhead irrigation equipment, and attack gnats in the larval stage in the container medium. It is well known that beneficial **mycorrhizal fungi** (which naturally colonize the root systems of *most* major horticulture, forestry, and agronomic plants) can increase plant disease resistance and help alleviate plant stress by enhancing the host plant water and nutrient uptake (32, 73). Mycorrhizae can also benefit propagation of cuttings, seedlings, and transplanting of liner plants (25, 33, 34, 110).

rhizosphere The zone of soil immediately adjacent to plant roots in which the kinds, numbers, or activities of microorganisms differ from that of the bulk soil.

The use of **biocontrol agents** (beneficial bacteria, actinomycetes, or fungi living and functioning on or near roots in the rhizosphere soil) to control plant pathogens in propagation is gradually occuring (73). These beneficial microorganisms suppress fungal root pathogens by antibiosis (production of antibiotic chemicals), by parasitism (direct attack and killing of pathogen hyphae or spores), or by competing with the pathogen for space or nutrients, sometimes by producing chemicals such as siderophores, which bind nutrients (such as iron) needed by the pathogen for its disease-causing activities. The inhibitory capacity of these biocontrol antagonists increases in the presence of mycorrhizal fungi, and in the absence of plant pathogens there is a stimulation of plant growth by bacterial antagonists; somehow these bacteria stimulate plant growth, but the mechanism is not known. Perhaps in the future, plant protection during propagation will be done by inoculation of bacteria or combinations of bacteria with mycorrhizal fungi, which come closest to simulating natural conditions of the plant rhizosphere (73). For some commercial nurseries, incorporating mycorrhizal fungi during propagation is now standard procedure (2008).

Cultural Control in IPM Cultural management continues to become more important in modern propagation systems with the loss of minor-use chemicals. In propagation, cultural control begins with the preplant treatment of soil mixes to suppress pathogens and pests. Other cultural control techniques include:

- sanitizing of propagation facilities
- suppressing pathogens and insect pests of stock blocks
- harvesting cuttings from stock blocks or containerized plants that are nutritionally fit and not drought stressed
- providing good water drainage to reduce the potential of *Phytophthora* root rot and other damping-off organisms
- reducing humidity to control *Botrytis*
- minimizing the spread of pathogens by quickly disposing of diseased plants from the propagation area, and
- hardening-off established propagules (96).

Cultural control in IPM includes:

- Stock plant management
- Media pasteurization
- Sanitation

Suppressing pathogens in propagation water is critical, since *Phytophthora, Pythium,* and *Rhizoctonia* are readily disseminated in surface water. Checking pathogens starts with the initial removal of suspended silt and solids, which can tie up chemicals being used to treat the water supply, a task most commonly accomplished by using a sand filterUltraviolet light irradiation is a nonchemical method of controlling pathogens, but water needs to be free of turbidity (suspended materials) that will shield some of the pathogens from the UV (Fig. 3–29). The most commonly used chemical treatments of irrigation water are with chlorination or bromination; one Australian nursery aims for a 4 ppm residual chlorine at the discharge of the irrigation water. They use a swimming pool chlorine test kit (15), such as easy-to-use, portable DPD color-indicator test kits (13). Current recommendations for chlorinated irrigation systems is to maintain a free chlorine level of 2 ppm (2 mg/liter) to kill *Phythiaceae* pathogens, and to increase the contact time to kill *Fusarium* and *Rhizoctonia* (20). A "free chlorine" level of 2.9 ppm is generally considered safe for most plants (106).

Selectrocide (chlorine dioxide) is also used for the control of algae and other microbial pests in greenhouse propagation irrrigation lines (68).

Preplanting Treatments of Mixes—Heat Treatment of Propagation and Liner Media Various Replanting Treatments of Mixes are Categorized as Follows

Pasteurization of Propagation Media. Propagation mixes such as bark, sand, and peat moss (14, 24) can contain pathogens and, ideally, should be pasteurized. The containers (bins, flats, pots) for such pasteurized mixes should, of course, have been treated to eliminate pathogens. Never put pasteurized mixes into dirty containers. New materials such as vermiculite, perlite, pumice, and rockwool, which have been heat-treated

BOX 3.12 **GETTING MORE IN DEPTH ON THE SUBJECT**

BENEFICIAL TRICHODERMA FUNGI

Trichoderma fungal species, which have plant growth-enhancing effects, independent of their biocontrol of root pathogens, have been reported to enhance the rooting of chrysanthemum cuttings, possibly by producing growth-regulating substances (76).

during their manufacture, need not be pasteurized unless they are reused.

Although the term soil *sterilization* has been commonly used, a more desirable process is **pasteurization,** since the recommended heating processes do not kill all organisms (Fig. 3–31). True sterilization would require heating the propagation media to a minimum temperature of 100°C (212°F) for a sufficient period to kill all pests and pathogenic organisms; all beneficial rhizosphere organisms are also killed by the process. Pasteurization of propagation media at lower temperatures with aerated steam is generally preferable to fumigation with chemicals.

After treatment with steam, the medium can be used much sooner. Steam is nonselective for pests, whereas chemicals may be selective. Aerated steam, when properly used, is much less dangerous to use than fumigant chemicals, for both plants and the operator. Chemicals do not vaporize well at low temperatures, but steam pasteurization can be used for cold, wet media.

Moist heat can be injected directly into the soil in covered bins or benches from perforated pipes placed 15 to 20 cm (6 to 8 in) below the surface. In heating the soil, which should be moist but not wet, a temperature of 82°C (180°F) for 30 minutes has been a standard recommendation because this procedure kills most harmful bacteria and fungi as well as nematodes, insects, and most weed seeds, as indicated in Figure 3–32. However, a lower temperature, such as 60°C (140°F) for 30 minutes, is more desirable since it kills pathogens but leaves many beneficial organisms that prevent explosive growth of harmful organisms if recontamination occurs. The lower temperature also tends to avoid toxicity problems, such as the release of excess ammonia and nitrite, as well as manganese injury, which can occur at high steam temperatures.

Electric Heat Pasteurizers. are in use for amounts of soil up to 0.4 m^3 (0.5 yd^3). *Microwave ovens* can be used effectively for small quantities of soil. They do not have the undesirable drying effect of conventional oven heating and will kill insects, disease organisms, weed seed, and nematodes.

Sanitation in Propagation In recent years, the importance of sanitation during propagation and growing has become widely recognized as an essential part of nursery operations. During propagation, losses of young seedlings, rooted cuttings, tissue-cultured rooted plants, and grafted nursery plants to various pathogens and insect pests can sometimes be devastating, especially under the warm, humid conditions found in propagation houses (80, 84). Ideally, sanitation strategies should be considered even in the construction phase of propagation structures (92).

Harmful pathogens and other pests are best managed by dealing with the three situations where they can enter and become a problem during propagation procedures:

- The propagation facilities: propagating room, containers, pots, flats, knives, shears, working surfaces, hoses, greenhouse benches, and the like
- The propagation media: rooting and growing mixes for cuttings, seedlings, and tissue culture plantlets
- The stock plant material: seeds, cutting material, scion, stock material for grafting, and tissue culture

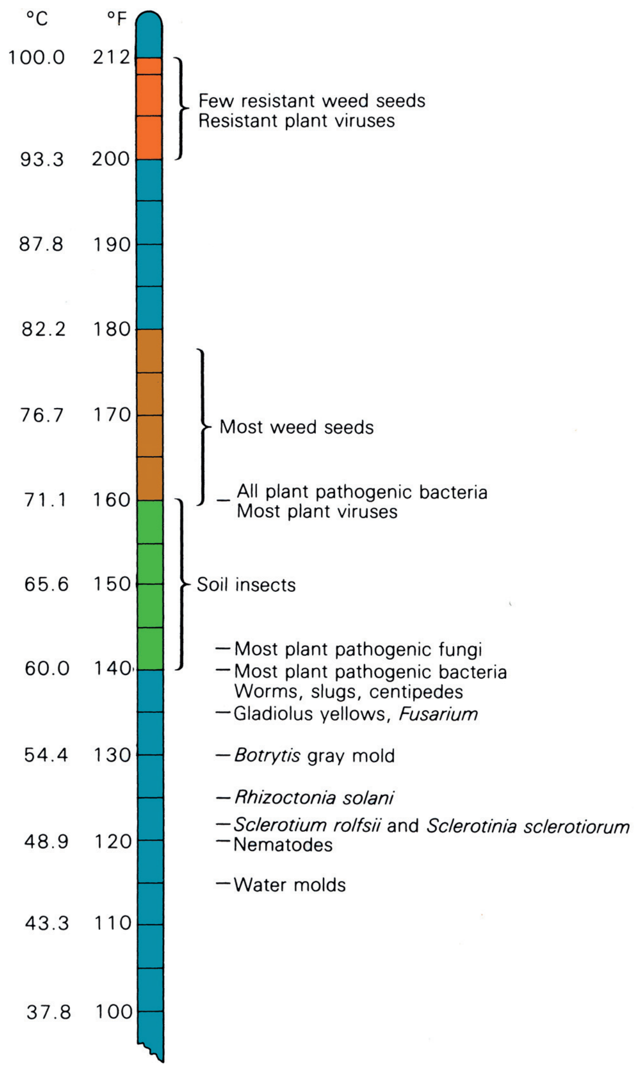


Figure 3–32
Soil temperatures required to kill weed seeds, insects, and various plant pathogens. Temperatures given are for 30 minutes under moist conditions.

If pathogens and other pests are suppressed in each of these areas, it is likely that the young plants can be propagated and grown to a salable size with minimal disease, insect, or mite infestations. Pathogenic fungi can best be controlled by using soilless mixes, pasteurizing propagation and growing mixes, considering general hygiene of the plants and facilities, avoiding overwatering, assuring good drainage of excess water, and using fungicides properly (81, 120).

Disinfection and Sanitation of Physical Propagation Facilities. Disinfection refers to the reduction of pathogens and algae, while sanitation refers to the level of cleanliness. The space where the actual propagation (making cuttings, planting seeds, grafting) takes place should be a light, very clean, cool room, completely separated from areas where the soil mixing, pot and flat storage, growing, and other operations take place. Traffic and visitors in this room should be kept to a minimum. At the end of each working day, all plant debris and soil should be cleaned out, the floors hosed down, and working surfaces washed with disinfectant solutions of sodium hypochlorite solution (Clorox), chlorine dioxide (Selectrocide), benzylkonium chloride (Physan 20, Green-shield), or pine disinfectant—diluted according to directions. Benzylkonium chloride is long-lasting and can be used for several days. Hydrogen dioxide (Zerotol, Oxidate) is a strong oxidizing agent used in sanitation of propagation facilities for the control of algae and pathogens (Fig. 3–33). Diluted household vinegar gives good control of algae and moss along walkways.

Flats and pots coming into this room should have been washed thoroughly and, if used previously, should be heat-treated or disinfected with chemicals (i.e., a 30-minute soak in sodium hypochlorite (Clorox) diluted one to nine). No dirty flats or pots should be allowed in the propagation area. Knives, shears, and

(a)

(b)

(c)

(d)


(e)

Figure 3–33
Some common chemicals for disinfecting propagation facilities and propagules (a) Benzylkonium chloride, (b) hydrogen dioxide, (c) bromine and (d) diluted sodium hypochlorite solution (household bleach) can be used for (e) disinfesting both propagation facilities and propagules. Diluted household vinegar can control algae and moss along walkways. Always follow directions and try small trials first.

other equipment used in propagation should be sterilized periodically during the day by dipping in a disinfectant such as Physan or Zerotol.

Mist propagating and growing areas in greenhouses, cold frames, and lathhouses should be kept clean, and diseased and dead plant debris should be removed daily. Water to be used for misting should be free of pathogens. Water from ponds or reservoirs to be used for propagation purposes should be chlorinated to kill algae and pathogens. Proper chlorination will control *Phytophthora* and *Pythium* in irrigation water and can help reduce the cost of preventive fungicide programs (13, 20, 28).

Maintaining Clean Plant Material. In selecting propagating material, use only seed and those source plants that are disease- and insect-free. Some nurseries maintain stock plant blocks, which are kept meticulously "clean." However, stock plants of particularly disease-prone plants, such as *Euonymus,* might well be sprayed with a suitable fungicide several days before cuttings are taken. Drenches of fungicides and/or Agribrom (oxidizing biocide) are sometimes applied to stock plants in the greenhouse prior to selecting explants for tissue culture.

It is best to select cutting material from the upper portion of stock plants rather than from near the ground where the plant tissue could possibly be contaminated with soil pathogens. As cutting material is being collected, it should be placed in new plastic bags.

After the cuttings have been made and before sticking them in flats, they can be dipped in a dilute bleach solution, or treated with Zerotol, Agribrom, Physan 20, or various fungicides for broad-spectrum control of damping-off organisms—before any auxin treatment. One Oregon nursery disinfects Rhododendron cuttings with Consan, followed by washing in chlorinated water (46). Agri-strep (agricultural streptomycin) helps suppress bacterial problems, and one biological control, *Agrobacterium* spp., helps prevent crown gall of hardwood rose cuttings (31). However, once a cutting or seedling *becomes infected with a bacterium, there is no effective control* other than rouging-outand destroying the plant propagule.

Best Management Practices (BMP)

To a very limited degree, through some improper pesticide usage and inefficient irrigation and fertility systems, the nursery and greenhouse industries have been nonpoint source polluters of the environment. As a whole, the horticultural industries are good stewards of the environment. The environmentally friendly plants they produce are critical to the well-being, nutrition, and welfare of people, and are vital to enhancing the environment (reduced air and noise pollution, reduced heat loads around houses and urban areas, which lower utility cooling bills, adding O_2 to the air, and contributing to the abatement of current high global CO_2 conditions, etc.).

With the increased environmental regulations facing plant propagators and as an offshoot of integrated pest management programs, the development of Best Management Practices or BMP has occurred (61, 133). To help preserve the environment and head off additional state and federal regulation, BMP are being developed by the nursery industry, governmental agencies, and universities. Plans are for the nursery and greenhouse industries to self-regulate by adapting BMP, which many propagators have already been practicing for years. The above list of the ten best management practices applies to nursery propagation and liner production systems. To date, recycled water is generally not used to propagate plants (liners and container plants are irrigated with recycled water mixed with purer well or surface collected water), but, in the future with the scarcity of irrigation water and increased urban population pressure to use limited water supplies, more nurseries will have to develop propagation systems that utilize recycled water. Recycled water can present considerable challenges, since high salinity, trace levels of herbicides, pesticides, and pathogens such as *Phytophthora* can occur (Fig. 3–29).

BOX 3.13 **GETTING MORE IN DEPTH ON THE SUBJECT**

THE USE OF CHLORINE IN PROPAGATION

Chlorine can be used as a **sterilant,** which destroys all organisms, and as a **disinfectant,** which selectively destroys pests (70). When chlorine is used as a pesticide, it prevents pests from entering the propagation environment and minimizes the need for more toxic pesticides. Pest reduction or elimination is a cornerstone of IPM programs.

Chlorine, in the form of laundry bleach (Clorox, etc.), is one of the most affordable and readily available chemicals (36). Chlorine is used to sterilize greenhouse benches, floors, and other surfaces in the propagation area. Chlorination is being increasingly used in recycled irrigation water for controlling pathogenic fungi, algae, and other pests.

Chlorine is available as:

a. a gas (Cl_2), which is liquefied in pressurized metal containers and bubbled as a gas into water, but Cl_2 gas is very toxic and its corrosive nature makes it very hazardous to handle

b. calcium hypochlorite [$Ca(OCl)_2$] is used for domestic water treatment and is commercially available as granulated powder, large tablets, or liquid solutions; and

c. sodium hypochlorite (NaOCl), the active ingredient of household bleach, which is the most common form of chlorine used in propagation. When a continuous supply of chlorinated water is needed, concentrated solutions of sodium or calcium hypochlorite are injected. Chlorine injectors must be installed with an approved check-valve arrangement to prevent back flow into the fresh water system (13), (70). Bleach solutions are generally calculated as percent bleach or percent sodium hypochlorite; but these are not the same, since a **10 percent bleach solution** (which contains one part bleach to nine parts water) is 10 percent of 5.25 percent sodium hypochlorite or equivalent to **0.52 percent sodium hypochlorite.** Household bleach is commonly used as a disinfectant by diluting one part bleach to nine parts water.

Many chemicals, as well as organic residue from plants and propagation medium, react with chlorine and reduce its effectiveness. Enough chlorine must be added to produce an effective concentration of "free residual" chlorine (Fig. 3–34). Factors affecting chlorine activity include:

a. concentration—water treatment requires around 2 ppm free residual chlorine (20), and the bleaching of propagation benches and containers requires a 10 percent bleach solution or 5,250 ppm

b. exposure time

c. organic matter—contaminated water containing residual from soaking propagation containers or dipping propagules uses up available chlorine more rapidly than a clean solution

d. water temperature

e. pathogen growth stage—chlorine kills fungal mycelium on contact but is not systemic so fungal spores and pathogens embedded in roots and walls of Styrofoam containers are much more difficult to kill; soaking materials before treating with bleach allows spores to germinate and mycelia to grow, making pathogens easier to kill, and

f. a pH—around 6.5 is most effective, (70). At pH 6.0 to 7.5 total chlorine is predominately in the form of hypochlorous acid (strong sanitizer), whereas at pH 7.5 and above, hypoclorite is dominant, which is a weak, ineffective sanitizer.

For successful chlorination, clean the container, bed, and propagule materials prior to chlorinating, monitor the chlorine solution, and ventilate the work area. Dilute chlorine solutions irritate skin and chlorine vaporization irritates eyes, nose, and throat. It is important that propagation managers know the legal exposure limits (OSHA) that workers can be exposed to chlorine.

There are some environmental concerns about the use of bleach as a disinfectant to surface disinfect cuttings and for the sterilization of tools and propagation work surfaces. The hypochlorite ion from bleach attaches to organic compounds in the soil and forms very stable chlorinated organic compounds. These compounds can be taken up by plant roots, get into the food chain, and may bioaccumulate in the body fat of animals and humans (80). An alternative disinfectant for propagation is hydrogen peroxide (H_2O_2). It can be used as a sterilant for both fungi and bacteria, has no toxic by-products (it breaks down to water and oxygen), and it has no residual effect in water or soil. Hydrogen peroxide can be purchased in bulk form (35 percent concentration rate). A recommended rate for surface disinfestation of plant material is 1 part

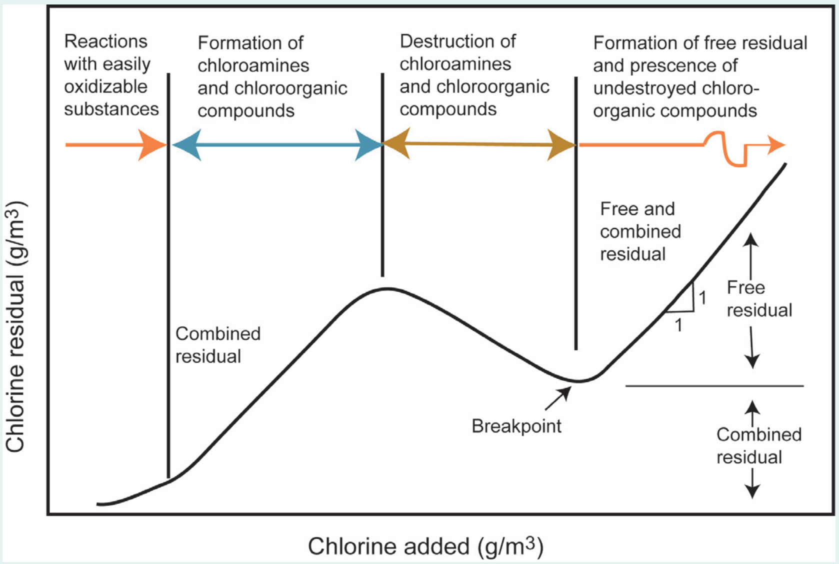


Figure 3–34
Many substances combine with chlorine to reduce its activity in solution, thus enough must be added to produce an effective concentration of "free residual" chlorine (70).

(Continued)

H_2O_2 (35 percent) to 100 parts water (80). Clorox (bleach) was found to be superior to hydrogen peroxide, Agrimycin 17 (agricultural streptomycin), or rubbing alcohol (isopropyl) in preventing the transmission of fire blight bacteria in pear trees (116).

Chlorine will continue to be used as an important disinfectant in propagation. Bleach is considerably cheaper than hydrogen peroxide, and with the dilute bleach solutions typically used in propagation, there should be little if any chlorine residual in tank solutions that are allowed to sit for several days (70). To be environmentally safe before discharging spent chlorinated water, test kits should be used to monitor residual chlorine levels, and local water quality officials can also be contacted.

POST-PROPAGATION CARE OF LINERS

Hardening-Off Liner Plants

Hardening-off or acclimating rooted propagules, seedlings, and tissue culture plantlets is critical for plant survival and growth. In commercial production, it assures a smooth transition and efficient turnover of plant product from propagation to liner production (Fig. 3–21) to finished plants in protected culture (greenhouses, etc.) or containerization and field production. This smooth transition and turnover of plant production units is essential in the marketing, sales, and profitability of plant manufacturing companies.

It is important to wean rooted cuttings from the mist system as quickly as possible (29). Reduction of irrigation and fertility in seedlings and plugs is done several weeks prior to shipping and/or transplanting to harden-off and ensure survival of the crop. Likewise, with acclimation of tissue culture-produced plantlets, light irradiance is increased and relative humidity is gradually reduced to stimulate the plantlet to increase photosynthetic rates and have better stomatal control. All of these ensure plant survival and a speedy transition when the acclimatized plant is shifted up and finished-off as a container or field crop. Acclimatization of liners is discussed in greater detail in Chapters 10 and 18.

Handling Container-Grown Plants

Irrigation Watering of container nursery stock is a major expense and environmental concern. In most operations, overhead sprinklers (i.e., Rainbird-type impact sprinklers) are used, although much runoff waste occurs. Watering of container plants by trickle, drip irrigation or low-volume emitters, results in less waste (121), and is becoming more widely used, particularly with plants produced in larger containers (Figs. 3–25 and 3–35). The development of solid-state soil tensiometers for the computer control of irrigation systems of containerized plants may help to increase water use efficiencies and decrease off-site pollution from runoff (17).

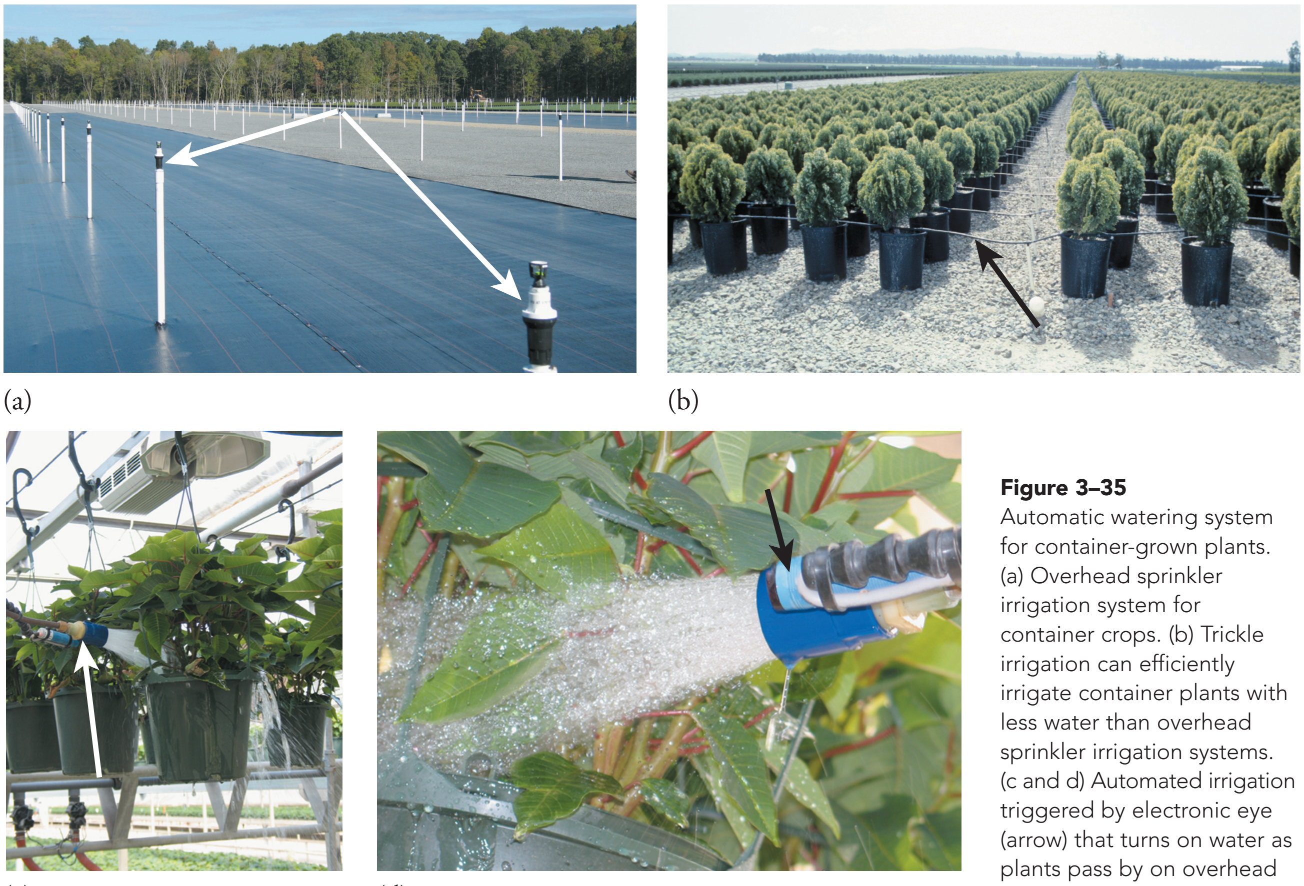
As part of Best Management Practices (BMP), many nurseries are switching to computer-controlled **cyclic** or **interval irrigation (pulse irrigation)** with impact sprinklers. Rather than manually turning on valves to run irrigation for 60 minutes, an environmental-control computer is programmed to precisely run the irrigation system three times daily at 5 to 10 minutes per cycle (123). Since most water is absorbed by the containers within the first 5 minutes, cyclic or pulse irrigation uses less water, greatly reduces water and fertility runoff, and lowers the amount of fertilizer needed in the fertigation system.

Flood floor systems for producing containerized plants and stock-plants for cuttings was discussed earlier in this chapter (Fig. 3–8).

BOX 3.14 **GETTING MORE IN DEPTH ON THE SUBJECT**

NURSERY BEST MANAGEMENT PRACTICES (BMP) (133)

- Collect runoff water when injecting fertilizer.
- Do not broadcast fertilizer on spaced containers.
- Do not top-dress fertilizer on containers prone to blow over.
- Water and fertilize according to plant needs.
- Group plants in a nursery according to water and fertilizer needs to minimize runoff.
- Monitor quantity of irrigation applied to prevent overwatering.
- Maintain minimal spacing between containers receiving overhead irrigation.
- Use low-volume irrigation for containers larger than 26 liter (7 gallon).
- Recycle runoff water



(a) (b) (c) (d)

Figure 3–35
Automatic watering system for container-grown plants. (a) Overhead sprinkler irrigation system for container crops. (b) Trickle irrigation can efficiently irrigate container plants with less water than overhead sprinkler irrigation systems. (c and d) Automated irrigation triggered by electronic eye (arrow) that turns on water as plants pass by on overhead conveyor system.

Fertilization Fertilizer solutions are usually injected into the irrigation system (fertigation) in commercial nurseries. Fertilizer may be supplied solely in controlled-release forms (Osmocote, Phycote, Nutricote, Polyon, etc.), or used in combination with fertigation (see page xx). After the container stock leaves the wholesale nursery, the retailer should maintain the stock with adequate irrigation until the plants have been purchased by the consumer. Controlled-release fertilizers added to containers leave a residual fertilizer supply (most retailers do not add supplementary fertilizer), and help maintain the plants until they are purchased by the consumer and planted in the landscape.

Root Development in Containerized Plants

When trees and shrubs from seedlings or rooted cuttings are grown in containers, roots often begin to circle on the outside of the rootball against the slick, smooth plastic container walls. If not mechanically controlled when the trees or shrubs are transplanted, circling roots may enlarge to the point of stressing or killing the plant by girdling (1). Internal walls of containers can be coated with copper compounds such as Spin Out, which is a latex-based paint containing copper hydroxide and a special formulated carrier (Figs. 3–23 and 3–25) that enhances root absorption of copper and temporarily inhibits root elongation (115), or containers can have special wall modifications as a means to reduce or prevent root circling during liner production and later container production. As shown in Figure 3–36, plants not properly air root-pruned or that are kept in containers too long will form an undesirable constricted root system from which they may never recover when planted in their permanent location. The plants should be shifted to larger containers before such “root spiraling” occurs.

The Ohio Production System **(OPS),** a system for rapidly producing container-grown shade trees (whips) in 1 year, compared with 3 years, also relies on copper-treated containers to control root growth. This eliminates or greatly reduces the need to root-prune when plants are upcanned to larger containers (114).

Using bottomless propagation and liner pots to **“air prune”** roots, judicious root pruning, early transplanting, and careful potting during the early transplanting stages can do much to encourage the development of a good root system by the time the young plant is ready

(a)

(b)

Figure 3–36
One disadvantage of growing trees and shrubs in containers is the possibility of producing poorly shaped root systems. (a) Here a defective, twisted root system resulted from holding the young nursery tree too long in a container before transplanting. (b) Such spiraling roots retain this shape after planting and unacceptable tree growth occurs. This is avoided by proper root training, beginning with air-root pruning seed flats during propagation.

for transfer to its permanent location. Plastic containers with vertical grooves along the sides tend to prevent horizontal spiraling of the roots (Figs. 3–20 and 3–22).

Alternatives to Traditional Production Systems

Several in-ground alternatives to container production in the field and conventional field production of bare-root and B & B (balled-in-burlap) trees and shrubs have been developed, including (a) the **pot-in-pot system** (43), in which a container is inserted into an in-ground plastic sleeve container, and (b) **in-ground fabric containers (grow bags)** (Fig. 3–25). Each of these methods can influence directional root development (1). The pot-in-pot, in-ground system involves sinking an outer or sleeve pot into the ground and inserting a second pot, which is the production pot that is harvested with the plant. The production container may have vertical ribs, or the interior walls are treated with copper to reduce root circling. The in-ground container system is a single container (unlike the pot-in-pot system) with rows of small holes along the container sides and bottom to enhance drainage.

In-ground fabric containers or grow bags are flexible, synthetic bags, which are filled with mineral soil and placed in predug holes in the field. The synthetic woven material of the bags limits most root penetration, and directs root growth to occur within the bag [more than 90 percent of the root system of conventional bare-root and balled and burlapped (B & B) plants are lost during digging]. Since the bag is placed in the ground, there is greater insulation of the root system against high and low temperatures (versus above-ground containerized crops), and the bag can be pulled out of the field, potentially reducing labor cost of traditional field techniques. This system does not work with all species, but has merits.

DISCUSSION ITEMS

1. What are some fundamental microclimatic and edaphic factors in the propagation environment?
2. How is light measured, and how is light manipulated in plant propagation?
3. Discuss the advantages and disadvantages of different types of plant propagation structures.
4. How does root zone heating save energy costs in propagation houses and enhance the rooting of cuttings?
5. Compare and contrast analog and computerized environmental controls of greenhouse propagation facilities.
6. What are some of the more popular covering materials for propagation houses?
7. What is closed-case propagation?
8. What kinds of containers are used for propagation and growing young liner plants?

9. Why is mineral soil rarely used in propagation and production of containerized plants?

10. Compare organic and inorganic media components used for propagation. What are peat-lite mixes?

11. How are pre-plant (preincorporated) and post-plant fertilization programs used in propagation and liner production systems?

12. How is salinity measured and controlled in irrigation water and container media used in propagation?

13. What are some potential problems in using recycled irrigation water for propagation?

14. How are accelerated growth techniques (AGT) used to enhance propagation?

15. Compare the broad definition of "pests" with insect pests.

16. What are "damping-off" pathogenic fungi? Give examples and indicate how they are disseminated.

17. How can integrated pest management (IPM) be utilized in propagation? Include the different areas of IMP and discuss the importance of the scouting system.

18. How are propagation equipment and facilities sanitized?

19. Why are best management practices (BMP) critical for environmental stewardship and the long-term profitability of the nursery industry?

20. What are some methods to "harden-off" liner plants during propagation and liner production?

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