2 Greenhouses and Protected Cropping Structures

2.1 Introduction

Protected cropping structure design is based on the local climate, crop and capital investment required and has features that will modify the environment suitable for high yielding production. This includes heat retention or loss, humidity control, supplementary light or shading, manual or computerized control of greenhouse variables and control over irrigation. Greenhouses for crop production through a cold winter period often differ considerably from structures used to produce crops in year-round hot, humid climates. Protected cropping structures can range from simple rain covers with open sides to fully enclosed, possibly twin skin, automated greenhouses and sophisticated glasshouses which are the basis of high-technology production.

A large proportion of greenhouse crops worldwide is still grown in relatively low-technology structures which represent a limited capital investment. These may be basic tunnel houses or wood- and plastic-roofed structures with little or no heating, forced ventilation or other forms of environmental control. These types of protected cropping structures are largely used in climates where heating is not required or only used for production during warmer times of the year when temperatures are suitable for crop growth (Fig. 2.1). The most extensive greenhouse industry worldwide exists in Asia where China has almost 55% of the world's plastic-clad greenhouse area and over 75% of the world's small plastic tunnels (Costa *et al*., 2004). The Mediterranean region has the second largest area of greenhouses in the world, most being plastic-clad structures with minimal environmental control. The main factors which influenced the expansion of plastic-clad structures in the Mediterranean region were a mild climate with a high amount of solar radiation year-round, improved transportation to markets across Europe, high heating costs of greenhouses in Northern European countries and the low cost of materials for the construction of greenhouses (Grafiadellis, 1999). The most common type of greenhouse in Spain is the Parral type consisting of a vertical structure of rigid wood or steel pillars on which a double grid of wire is positioned to hold the plastic film, allowing for stability in high winds (Teitel *et al*., 2012). These low-cost structures may be multi-span but can have issues with water condensation on the inside of the cladding, a lack of sufficient roof ventilation and reduced light transmission due to the low slope of the roof (Teitel *et al*., 2012).

While the Mediterranean region is largely dominated by plastic-clad structures, high-technology glasshouses are more concentrated in the lower light climate of the Netherlands which has more than a quarter of the total area under glass worldwide (Peet and Welles, 2005). The Dutch greenhouse industry is associated with the Venlo greenhouse, which is largely used for vegetable, cut flower and potted plant production with either narrow- or wide-span designs (Teitel *et al*., 2012). Older-style Venlo greenhouse designs often had gutter heights of 2.5–3 m; however, more modern structures have seen an increase in gutter height to 5–7 m allowing for a greater degree of environmental control (Teitel *et al*., 2012). Venlo greenhouses are typically clad in glass, allowing for a high degree of light transmission, although some may be clad in other materials such as rigid plastic. High-technology structures are typically set up where the climate requires a greater level of environmental control for maximum yields and where

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Fig. 2.1. Tomato greenhouse sited in a tropical climate.

markets have been developed which will pay premium prices for quality fresh produce.

2.2 Glasshouses and Plastic Greenhouses

Many climates experience lower air temperatures during the winter months, but with summer temperatures which are still higher than optimal and varying levels of radiation. In these conditions, greenhouses must be able to be economically heated in winter and cooled in summer. When cropping is concentrated only during the warmer months of the year, basic, unheated structures may be used for many crops. In these environments pad- and fan-cooled, plastic greenhouses with top vents and winter heating are used for many common crops such as tomatoes, capsicum and cucumber. Greenhouse designs for temperate and mid-latitude climates are designed to modify the environment for both seasonal and year-round variations in temperature. Efficient heating of air inside the greenhouse with insulation and maintaining this heated air becomes the main consideration. Traditionally, heated pipes carrying hot water from boilers were the main method of heating and this is still effective for many crops. Heating may also use a system of plastic ducts at floor level which deliver warm air to the base of the plants. Greenhouses in temperate-zone climates usually incorporate fully clad side walls, roof and often side vents allowing large ventilation areas, computer control of environmental equipment such as heaters, shade or thermal screens, fogging and vents. Using modern plastic films and building technology has seen the development of twin layers of plastic which are inflated, offering improved insulation and a greater degree of environmental control.

Greenhouses sited in cold temperate and high latitude climates have large variations in day length and temperature. Day temperature may be below freezing for a large part of the year with very short day lengths, while coastal regions have short, mild summers with extended day lengths. Protected cropping structures for this type of climate require solid walls with well-built, comparatively steep solid roofs to carry snow loading which may otherwise collapse plastic-film-clad structures. Greenhouse structures in cold climates may have double-insulated walls and retractable thermal screens to assist with heat retention at night. Use of supplementary, artificial lighting is more common in these climates as low light intensity, snowfall and short days severely restrict incoming natural light levels for much of the year.

Greenhouse designs are varied; however, large industrial-scale installations often use gutter-connected greenhouses which allow for relatively easy expansion of the greenhouse as required. Gutter-connected greenhouses are composed of a number of bays running side by side along the length of the structure with the production area inside completely open and available for large-scale cropping, some of these structures are more than a hectare in size. The roof consists of a number or arches which are connected at the gutters where the bays meet (Fig. 2.2). Modern greenhouses have a high gutter height to allow for the production of long-term crops such as tomato and capsicum which may reach as tall as 3–4 m and to allow a greater degree of environmental control (Fig. 2.3). Gutter heights in modern greenhouses are often 5–6 m and claddings range from glass panels, polycarbonate sheets to single or double polyethylene film skins.

2.3 Closed and Semi-Closed Greenhouse Structures

A closed greenhouse structure completely eliminates ventilation and air exchange with the outside environment, thus must provide sufficient heating, cooling, humidity removal and CO_2 for maximum crop growth. The main objectives of a closed greenhouse system are to maintain high levels of CO_2 for crop photosynthesis, reduce pesticide requirements by preventing pests from entering the structure and save on energy costs for heating. While closed greenhouses appear to have significant advantages in cooler climates, the high requirement for cooling control during warm summer conditions

Fig. 2.2. Greenhouse design which consists of a number of connected arches.

Fig. 2.3. Modern greenhouses have a high gutter height to facilitate the growth of tall crops and give a good degree of environmental control.

and control of humidity are reported as being not economical to carry out (Zaragoza *et al*., 2007; van't Ooster *et al*., 2008). Closed greenhouse systems often harvest and store latent heat for use at night or when required for temperature control. Semi-closed greenhouses do not have 100% closure and maintain some air exchange with the outside environment largely for humidity removal; however, this percentage is still relatively low. Dennehl *et al*. (2014) reported that semi-closed greenhouses produced crop photosynthesis and yield increases of 20% or higher, while conferring advantages such as an improved degree of control of the greenhouse environment, reduced water requirements and reduced entry of pests and disease.

2.4 Passive Solar Greenhouses

Passive solar energy is widely used to heat greenhouse structures and requires no specialized photovoltaic (PV) cells. Passive solar heating is simply the collection of heat energy inside a greenhouse due to sunlight and this process can be effective for extending the growing season. Eighty-five per cent of the total greenhouse energy requirement is typically used for heating in cold climates, which is a function of the high heat loss from most greenhouse cladding materials (Harjunowibowo *et al*., 2016). Passive heating technology uses thermal or heat banks which absorb the heat of sunlight during the day and re-radiate this into the growing environment at night to keep temperatures higher than those outside. Another example of a passive solar greenhouse still widely in use in China consists of a thick wall and partial roof on the north side of the structure that acts as a heat sink, absorbing solar energy during the day and releasing this at night, where a thermal blanket is used over the plastic cladding to retain the heat (Tong *et al*., 2009).

A more advanced form of heat storage is the use of phase-change materials (PCMs) which require less space and have a higher heat capacity than traditional heat-bank materials such as water or concrete. Phase change refers to materials that change between a liquid and solid when absorbing or releasing heat and include a range of substances such as oils, paraffin and salt hydrates. PCMs are most suitable for passive temperature control in regions where there are large variations between outside day and night temperatures and can be used for both heating and cooling when required. Najjar and Hasan (2008) found that the use of a PCM inside a greenhouse to absorb excess heat decreased temperature by 3–5°C.

Thermal screens which are pulled across inside the top of the greenhouse to retain daytime heat well into the night are also part of using solar heating efficiently alongside energy-efficient claddings and heat-retentive measures such as inflatable twin-skin greenhouse designs. Heat-bank materials and thermal screens may not be sufficient to provide optimal temperature control in some climates; however, they supplement the energy cost of other types of heating systems. More advanced methods of passive solar energy collection are being developed which not only store and release heat, but also can contribute the cooling required inside a greenhouse structure (Dannehl *et al*., 2014).

2.5 Sustainable Greenhouse Design

The development of sustainable greenhouse structures and systems has become of increasing importance over recent years, driven by consumer awareness and concern over food production methods and the requirement for growers to remain economically competitive. Greenhouses provide the environmental control required to increase yields and quality of produce; however, this requires the use of considerable amounts of energy and generates large quantities of wastes to be disposed of (Vox *et al*., 2010). The installed energy power load of a greenhouse structure depends on local climate conditions and has been estimated at 50–150 W/m^2 in southern regions of Europe, 200–280 W/m^2 in northern and central regions of Europe and up to 400 W/m^2 (heating, lighting and cooling) for complete microclimate conditioning of a greenhouse structure (Campiotti *et al*., 2012). There are an estimated 200,000 ha of greenhouses within Europe alone, of which about 30% are permanent structures and use fossil fuels for environmental control (Campiotti *et al*., 2012). With concerns over the reliance on non-renewable fossil fuels and CO_2 emissions, sustainability directives have become more focused on new greenhouse designs which incorporate new technology in cladding materials and use solar, geothermal and solid biomass energy sources.

While reducing energy use and CO_2 emissions are the main sustainability issues within the greenhouse industry, other factors include the safe disposal of waste plastics and claddings after use alongside overall waste reduction, reduction in water and fertilizer usage, prevention of drainage into groundwater and soil preservation, significant reduction in agrochemical use, effective management of the greenhouse environment by maximizing the use of solar radiation, air temperature, humidity and CO_2, and the use of renewable energy sources (Vox *et al*., 2010). Energy conservation in protected cropping can be achieved with use of the correct structure design for the local climate, incorporation of improved glazing materials, more efficient heating and distribution systems and new technologies in climate control, thermal insulation and overall greenhouse management. Locating greenhouses in regions with higher light, and in sheltered areas or installing windbreaks, can also assist with prevention of wind-induced heat loss and thus energy requirements for heating.

Thermal screens help retain heat by acting as a barrier between plants and the roof and also reducing the volume of air to be heated at night. Thermal screens are also used in summer to shade the crop from intense sunlight and thus reduce the energy required for cooling. Use of computerized environmental control inside greenhouse structures can also give improved energy efficiency by integrating heaters, fans, ventilation and humidity, controlling the activation of thermal and shade screens, and linking environmental inputs to irrigation timing.

2.6 Cladding Materials

Climate and cladding material determine the most suitable structure for greenhouse design, with many low-cost greenhouses utilizing a single span with plastic cladding. From the 1950s and 1960s onwards, the development of widespread, low-cost plastic technology allowed lighter and more diverse greenhouse frame structures to be used in greenhouse design where previously heavy glass panels required considerable support and framework. Low-cost materials such as wood and bamboo were able to be formed into plastic-clad, often unheated, greenhouse structures which rapidly increased in number in milder climates. Plastic films are often modified to allow maximum light transmission but conserve heat loss to the outside environment, and most incorporate some degree of UV resistance to breakdown or anti-condensation factors. Films with selectivity to certain wavelengths of radiation and co-extruded films made up of different layers of materials are becoming more common. Rigid plastic coverings are more expensive than film claddings, and include fibreglass, polycarbonate and polyvinyl chloride (PVC) panels. Glass claddings are used extensively where crops benefit from increased light transmission that this cladding provides and are common in structures such as the Dutch Venlo greenhouse design.

New technologies in greenhouse cladding films are continuing to be developed and many of these have distinct advantages for hydroponic cropping. The plastic materials most commonly used for greenhouse claddings are based on low-density polyethylene (LDPE), ethylene vinyl acetate (EVA) and plasticized PVC (Castilla, 2013), and these may be modified with additives for specific purposes. Plastic films permit photosynthetically active radiation (PAR) to penetrate into the greenhouse for crop photosynthesis; however, nearly half of the solar radiation energy is near-infrared radiation (780–2500 nm) which is a direct source of heat (Liu *et al*., 2018). The transmission of near-infrared radiation raises the temperature inside the greenhouse, which may be beneficial in cooler winter climates, but is undesirable in tropical and subtropical regions. Claddings which reduce the transmission of near-infrared wavelengths have been trialled under warm-climate cropping conditions and it was found that temperatures can be reduced by 2–3°C compared with a greenhouse with a conventional polyethylene film (Liu *et al*., 2018). It had been previously reported that issues with near-infrared blocking films included a reduction PAR levels entering the greenhouse for photosynthesis when infrared-blocking compounds in the film were increased (Teitel *et al*., 2012). Near-infrared selective compounds can be incorporated into the cladding in a number of ways: as permanent additives to the cover material, as a temporary coating to the surface applied seasonally or as movable screens. Near-infrared radiation control has proven to be highly effective when diamond microparticles are used as a coating, giving a high transmittance with the shorter visible wavelengths and high reflectance in the near-infrared region (Aldaftari *et al*., 2019). Temporary coatings and mobile screens offer the advantage of being applied during summer when heat reduction is required and removed to allow maximum heating under cooler conditions. Further improvements in the optimal qualities of greenhouse cladding films are expected to be made which allow further modification of the greenhouse environment and maximize crop responses to incoming radiation levels.

Other additives incorporated into greenhouse cladding films are those which alter the spectral quality of light entering a crop. These additives are designed to block or absorb some wavelengths that are not used by plants and transform them into wavelengths used in photosynthesis (Castilla, 2013). Some cladding films have been developed that can alter the ratio of red to far-red wavelengths which influences certain plant photomorphogenic processes. Cladding additive compounds which block UV radiation (280–400 nm) have been studied with respect to how this might affect the behaviour of certain insect pests by limiting their vision. It has been found that under UV-blocking greenhouse films and netting, lower numbers of whitefly (*Bemisia tabaci*), thrips (*Ceratothripoides claratris*) and aphids (*Aphis gossypii*) entered and were found in greenhouses compared with ones with higher UV intensity (Kumar and Poehling, 2006). Insect-vectored virus infection levels were also found to be significantly lower under UV-blocking claddings as compared with non-blocking greenhouse films (Kumar and Poehling, 2006). Other studies have found similar results, with the number of whiteflies trapped on sticky yellow plates under UV-absorbing film to be four to ten times lower and that of thrips ten times lower than the number trapped under regular films (Raviv and Antignum, 2004). While numbers of insect pests such as whitefly, aphids and thrips may be reduced under UV-blocking films, the effect on crop yields has shown no differences for crops such as tomatoes, capsicum and cucumber; however, it may reduce the purple/violet coloration of certain cut flower species (Messika *et al*., 1998).

Apart from spectrum-selective cladding films, greenhouse plastics may be manufactured to diffuse light so that leaf burning under high radiation levels may be prevented in certain climates. Radiation is considered to be diffuse when it deviates by more than 2.5° from the direct incident radiation (Teitel *et al*., 2012), with this referred to as 'turbidity'. Diffuse radiation increases the light uniformity at crop level and has been shown to increase yields in certain climates (Castilla and Hernandez, 2007). Diffuse light allows more radiation to be intercepted by the crop, particularly in the lower levels of the canopy, so that the overall assimilation rate is higher. Cladding films can provide turbidity up to 80%; however, lower percentages may be just as effective. Studies have shown that the composition of plastic greenhouse cladding films can not only affect yields but also quality of hydroponic produce. Petropoulos *et al*. (2018) found that cover materials significantly affected tomato fruit quality, particularly the sugar and organic acid contents as well as tocopherols and pigments, with higher sugar contents found under single three-layer film and highest organic acids under seven-layer LDPE film and single three-layer film.

Greenhouse cladding films may also have additives incorporated into the polymers which modify the surface tension of the film; this may be to either repel dust on the outside of the structure or avoid issues with water droplets caused by condensation on the inside. The anti-drip properties are obtained by modification of the surface tension of the cladding film (Giacomelli and Roberts, 1993). As condensation forms, the water remains in a continuous sheet which flows towards the edge of the roof for collection, rather than forming droplets which fall on to the crop below increasing the risk of disease. This effect is achieved by addition of anti-fog additives such as surfactants into the plastic film material; however, this anti-fog effect reduces over time as the surfactants are extracted by the condensed water (Fernandez *et al*., 2018).

While improved technology in greenhouse films continues to develop over time, plastic films still have a limited lifespan and require replacement, with most having a minimum useful life of 24 months (Giacomelli and Roberts, 1993) and many lasting for 3–4 years before replacement. Degradation of plastic greenhouse claddings is typically caused largely by exposure to UV radiation, despite the use of UV inhibitors incorporated into the film material. Films also lose transmittance over time through the action of dust, pollution, weathering and pesticide usage. The use of polyethylene films which are co-extruded with different layers can improve UV degradation and the mechanical properties of the film (Giacomelli and Roberts, 1993), giving a more versatile product and multiple beneficial properties.

Plastic films are the most widely used of the greenhouse materials due to their flexibility, lightweight nature and low costs; however, rigid structured plastics are strong and have a considerably longer life than most cladding films. Rigid sheets used for greenhouse cladding may be made from acrylic, fibreglass, polycarbonate and PVC. Polycarbonate and fibreglass sheets are typically either corrugated or reinforced and have high light transmission. Most also have a usable life of 10 years before light transmission declines. The main advantage of rigid plastic claddings is the fact these are lighter in weight than glass, with a high diffusion of light and high resistance to impacts and weather events such as hail. Rigid claddings also contain UV protection and allow transmission of short-wave infrared radiation which is an advantage in warmer climates and for summer cropping (Castilla, 2013).

Traditionally, before the development of plastics, all greenhouses were clad in glass panes which had a long lifespan and did not result any loss of light transmission over time provided cleaning was carried out. Glass maximizes light transmission, allowing all wavelengths (320–3500 nm) apart from a small portion of the UV to pass through, but is more expensive than plastic films and requires a stronger structure for supporting the cladding. Glass panels of various sizes may be used; however, large panels reduce structure shading and provide more light for the crop. For this reason, glasshouses are still popular in North-West Europe because of the economic advantage of higher light transmission (Peet and Welles, 2005).

Future developments for greenhouse cladding films are likely to include longer-lasting materials which retain high levels of light transmission over their usable lifespan, thus reducing volumes of plastic waste from the greenhouse industry. Other challenges include the development of improved thermal properties of claddings which retain more heat without the loss in light transmission that typically occurs. The use of more specific UV filters which limit infestation by pests without affecting pollinator activity is another likely development in the greenhouse industry (Fernandez *et al*., 2018).

2.7 Screen Houses, Net Houses, Shade Houses, Rain Covers and Other Structures

In climates with sufficient warmth for year-round cropping, screen/net or shade houses or open-sided rain cover structures are commonly used for plant production. For certain low-light species, shade houses may be utilized in a wider range of climates to modify the environment without completely controlling it. In dry, tropical desert environments where temperatures can be extremely high all year round with low humidity and minimal rainfall, the main environmental threat is wind carrying dust and sand. In these climates protected cropping structures may consist of poles set deeply into the ground, covered with high-tensile steel wires to from a basic framework over which a single layer of fine insect mesh is stretched and secured around the edges. This forms a shaded and insect-proof structure which lowers both excessive light and temperatures to more optimal levels with internal humidity increased via fogging and misting and air-movement fans promoting transpiration from the crop. In the humid tropics, which experience warm to hot air temperatures all year accompanied by high rainfall, light levels are often inconsistent and combined with short day lengths, and insect pressure is extremely high. Commonly utilized protected cropping structures under these conditions are often simple overhead rain covers with insect mesh sides. A saw-tooth greenhouse design allows good ventilation of hot air inside the greenhouse during clear days. Use of evaporative cooling under tropical climates is frequently not possible due to naturally high air humidity.

2.8 Screen and Shade Nets

Screen and shade houses may be covered in a diverse range of cladding materials depending on the degree of environmental modification required or other objectives such as insect screens for the exclusion of virus-transmitting insects and birds and a reduction in pesticide requirements. Shade screens and netting do not provide the degree of microclimate modifications achieved with plastic- and glass-clad greenhouses; however, they are an efficient tool for hydroponic cropping in many regions. Shading screens and nets modify the intensity of light entering the structure as well as air and root-zone temperature, humidity, CO_2 concentration, air turbulence and ventilation rate, and they also protect from hail and wind damage (Fig. 2.4). Compared with unprotected cultivation, screens and net houses reduce solar radiation by 15–39% and air velocity by 50–87%, increase relative humidity by 2–21%, and decrease air temperature by 2.3–2.5°C and evapotranspiration by 17.4–50% (Mahmood *et al.*, 2018). Screens and net claddings fall into a number of different categories: the most common are composed of materials such as high-density polyethylene (HDPE), polypropylene and aluminized screens, as well as screens of different colours (black, white, blue, red and green), different levels of shading (10–50%) and mesh sizes.

More sophisticated screens and net claddings incorporate the use of spectral absorption for insect control, aluminized screens for reducing frost damage and photo-selective screens for modifications in fruit and vegetable attributes (Mahmood *et al.*, 2018).

2.9 Low Tunnels and High Tunnels

Low and high tunnels are low-cost, plastic-covered, arched structures which differ in height depending on the crop being produced. Low tunnels, also termed ‘row covers’, are a form of temporary plasticulture structure, less than 1 m in height and are also referred to as ‘cloches’ (Fig. 2.5). These may be constructed with wire or galvanized metal frames and clips, or double-wire systems which sandwich the plastic film in place and allow it to be slid up at the sides for access to the plants and ventilation control. Older-style low tunnels may be constructed from timber frames with plastic attached to the top and sides.

High tunnels, also known as ‘hoop houses’, ‘poly tunnels’ or ‘poly houses’, are of sufficient height to walk in so that crops may be planted, trained and harvested from within. While high tunnels are a form of low-cost greenhouse, these are defined as being a ‘free-standing or gutter connected structure, typically without any form of heating, cooling or

Fig. 2.4. Shade houses modify the intensity of light entering the structure as well as air and root-zone temperatures while providing protection from hail and wind damage.

Fig. 2.5. Low tunnels or cloches sited on NFT benches.

electricity, using natural or passive ventilation' (Fig. 2.6). The main objective of high tunnels is to provide a low-cost method of warming the air and protecting crops from wind and rain which extends the growing season and improves produce quality for many crops, as they do not provide the degree of environmental control of modern greenhouse structures. Taller crops such as tomato, capsicum and cucumber may be cultivated in high tunnels year-round, although a lack of ventilation and temperature control can create issues mid-summer and mid-winter in many climates. Although high tunnels may have wind-up sides for natural air exchange and ventilation, warm air can rise and become trapped in the arched roof of the structure causing excessive heat build-up (Fig. 2.7). Cladding films for both high and low tunnels are similar, including EVA, PVC and standard greenhouse-grade polyethylene. Low tunnels in particular may be covered with perforated plastic film to facilitate air movement and ventilation in frames which do not allow the plastic sides to be raised and lowered during the day. These types of high and low tunnel structures may also be covered with materials other than plastic film including shade cloth, insect mesh, the spun-bounded polyester or polypropylene used in floating row covers and frost cloth depending on the species being grown, the climate and the type of protection required. Main crops grown worldwide in high tunnels are vegetables, including tomato, capsicum, cucumber, muskmelon, lettuce, squash and aubergine; however, other crops include small fruits such as strawberries, tree fruits and cut flowers.

2.10 Hot Beds and Cold Frames

Cold frames are essentially miniature greenhouses used to extend the growing season, often to raise early transplants in spring. A traditional cold frame was usually

Fig. 2.6. High tunnels are a form of low-cost greenhouse using natural or passive ventilation.

constructed from brick or timber with a sloped, glass-roofed top, built low to the ground. Historically these were often part of the foundation brickwork along the southern wall of larger greenhouse, used to harden off seedlings before planting out. Cold frames are heated only by the sun and may be ventilated under warmer conditions by lifting of the hinged roof. While raising and hardening off seedlings are the main purposes of cold frames, they may also be used to grow cold-hardy winter vegetables, providing solar warming and protection from wind and heavy rain.

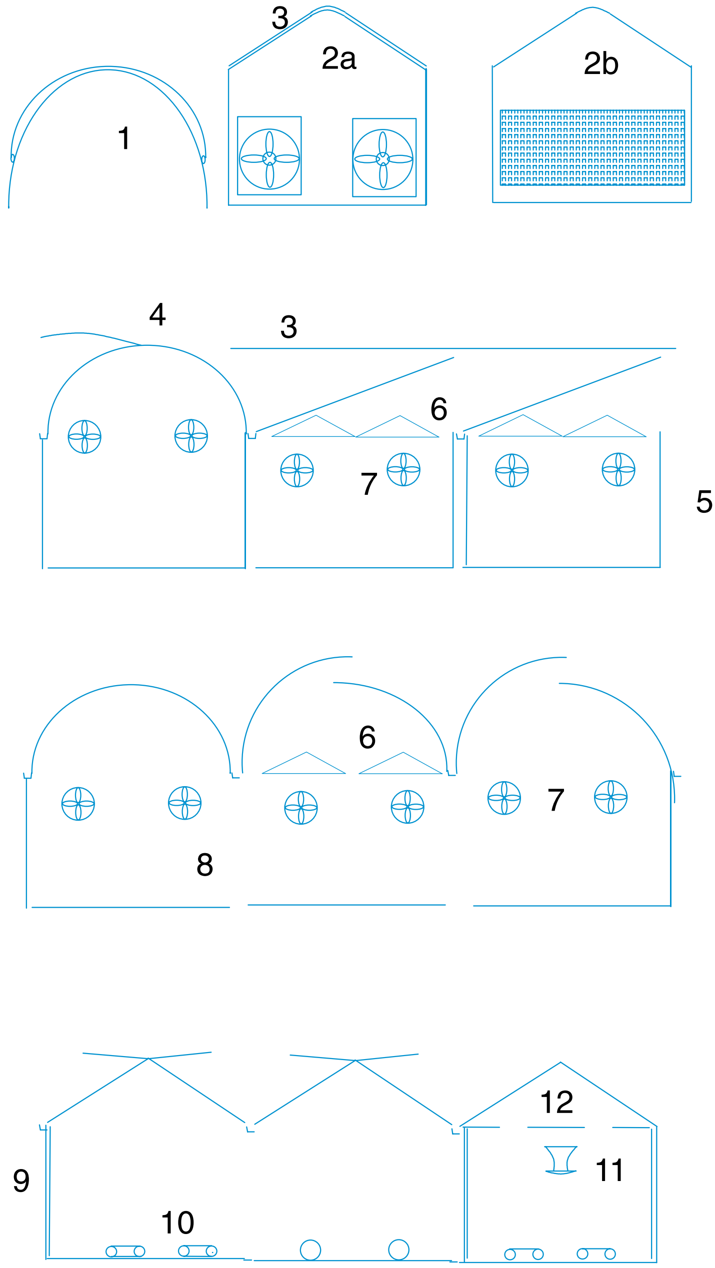

Fig. 2.7. Types of greenhouse structures: 1, tunnel house with cover partially retracted for ventilation; 2, gothic arch greenhouse with fan (a) and pad (b) evaporative cooling; 3, external shade cover; 4, high tunnel with adjustable roof ventilation; 5, sawtooth greenhouses with permanent roof ventilation; 6, evaporative misting; 7, horizontal air-movement fans; 8, gutter-connected high tunnels with and without permanent ventilation; 9, Venlo-style glass or plastic greenhouse with adjustable roof with or without side ventilation; 10, heating pipes (hot water) or ducted hot air; 11, vertical air-movement fan; 12, thermal screens across roof and sides.

Hot beds or hot boxes are similar in construction to cold frames; however, while cold frames are largely heated by the sun, hot beds use other forms of increasing the temperature inside the structure and are more suitable for warm-season plants such as tomatoes, melons, capsicums and aubergines. Heating of hot beds was traditionally carried out with pits or troughs of composting organic matter such as manure, placed directly under the base of the hot bed. The process of decomposition released sufficient heat to assist with germination and growth of seedlings. Electric hot beds use insulated heating cables to provide heat as required, while flue-heated structures used the burning of various fuels to create heat which was transferred into the hot bed. Steam and hot water heating pipes are also used in hot bed structures, particularly when associated with an adjacent heated greenhouse.

2.11 Floating Mulches, Row Covers, Cloche Covers, Direct Covers and Frost Cloth

Floating mulches, also known as 'direct covers' or 'row covers', are lightweight, inexpensive, easy-to-install covers placed directly over a crop which help trap heat from the sun, insulate against frost and act as a barrier to wind, insects and other predators. While a range of fabrics and plastics may be used in cover construction, the most common are perforated polyethylene approximately 1 mm thick or spun-bounded polyester or polypropylene which is manufactured into several different weights for varying usage. Perforated plastic covers have a pattern of holes in the material which assist ventilation and hence facilitate air movement through the cover and around the plants. The disadvantage of perforated covers is that heat may be lost rapidly via ventilation at night and small insects may gain entry to the crop below. Spun-bounded covers are manufactured from a thin mesh of synthetic fibres, usually white in colour, which retain heat from the sun and exclude insects while allowing light and rain to penetrate. Cover weight can range from 10 to 70 g/m^2, with heavier covers used for frost protection (referred to as 'frost cloth') which may be permanent in winter or used only at night, and lighter weights for insect and bird exclusion as these have little heat-retentive properties. Floating row covers are manufactured in a range of widths and roll lengths depending on the crop they are to be applied to.

Due to their lightweight nature, row covers sit lightly over the surface of most crops and do not require any support structures, hoops or cloche frames to be attached to.

Apart from providing a protected and more favourable microclimate for early- and late-season crops and frost damage prevention in winter, floating row covers are commonly used for exclusion of flying insects which are major pests of certain plant species. It has been found that polypropylene floating covers almost completely excluded aphids and tarnished plant bugs from crisphead lettuce (*Lactuca sativa*), pests which cause significant plant damage (Rekika *et al*., 2009). Other insect pests which are effectively controlled by lightweight floating row covers include brassica crop looper caterpillars and cabbage worms, flea beetles on aubergine, radish and other plants, sweet potato whitefly (*B. tabaci*), vegetable leaf miner (*Liriomyza sativae*) on cantaloupe (Orozco-Santos *et al*., 1995) and many other flying insect pests which infest and damage crops, spread virus disease or lay eggs on foliage.

2.12 Greenhouse Site Planning

When planning a hydroponic greenhouse operation, there are many factors to consider aside from the type of structure, cladding, dimensions and level of technology. The site selected requires certain characteristics essential for the operation and running of a hydroponic greenhouse business. These include access to a suitable, high-quality water supply, site drainage and a level area with good access via roads and driveways. Sites which have some degree of shelter such as natural or artificial shelter belts are preferable where high winds are common as these can cause considerable damage to greenhouse claddings and structures. Shading from hills, neighbouring buildings and other structures needs to be considered so that maximum light levels can be obtained. Utilities such as electricity are required for most hydroponic operations and additional land may be necessary for water storage (tanks or reservoirs), waste disposal, pack-house facilities and storage buildings. Greenhouses should be sited with the correct orientation and with room for future expansion.

When designing a greenhouse operation, consideration needs to be given to the materials flow, internal movement of staff and produce, and efficient layout of all the facilities required. A commercial operation aims to optimize food safety and other risks by designing a system where materials and inputs move from the least hygienic areas (inwards goods bays, storage areas, and rubbish and waste receptacles) to the cleanest areas – storage of produce and outwards shipping bays where the final product is transported from the operation. This helps prevent cross-contamination between areas of the greenhouse operation and maintain hygiene in the harvested product. Inside the greenhouse, management and labour for hydroponic crop production are a major expense, thus any means to increase labour productivity and improve labour management are beneficial (Giacomelli, 2007). Larger greenhouses such as gutter-connected structures are generally more labour efficient than a number of smaller, stand-alone structures and centralized preparation areas for staff are also beneficial. Commercial greenhouses are divided into bays and typically designed with a wide central aisle from which rows of plants run. The central aisle provides passage for staff, harvested produce and other supplies into and out of the greenhouse. A head house is often incorporated into the greenhouse structure where facilities such as the pump room, nutrient testing and supplies are contained; this area may also serve as a grading and packing facility for harvested produce.

2.13 Windbreaks

Windbreaks may be installed surrounding protected cropping structures such as greenhouses, tunnels or shade houses to assist with prevention of damage by wind and to lower the heat loss from these. Windbreaks are particularly important for providing shelter for outdoor or cloche-covered hydroponic bench systems and provide some degree of microclimate modification. The improvement in microclimate that windbreaks provide includes less disease incidence, warmer temperatures, high humidity and more favourable conditions for the activity of pollinators such as bees and other insects. In arid and desert regions, windbreaks may be installed to assist with the prevention of wind erosion of soils, contamination of produce with wind-blown dust and particles as well as crop protection.

Windbreaks may be constructed from a range of materials, the most common being timber, metal or concrete structures and wire framework which support woven or knitted polyethylene or polypropylene windbreak material. On a smaller scale, windbreaks may be constructed from bamboo, brush stick screens, wooden stakes, canes or other natural materials. Live or natural windbreaks consist of a number of different tree species, selected, trimmed and maintained to provide the correct degree of wind prevention. Windbreak species include eucalyptus, cypress, casuarinas, poplar, oak, maple, acacia and willow; however, many other plant types may be used depending on local availability and climate. A combination of both artificial and natural windbreaks may be used for maximum efficiency in some circumstances. For windbreaks to be efficient and prevent damage the porosity or permeability of the material must be in the range of 40–50%, this slows the wind and reduces its intensity. A high-density or solid windbreak generates unwanted turbulence and eddies on the crop side of the structure, whereas allowing some permeability creates the correct degree of protection. The horizontal range of wind reduction by a windbreak, expressed in percentage, is proportional to its height and is practically independent of wind speed (Wittwer and Castilla, 1995).

2.14 Outdoor Hydroponic Systems

Most hydroponic production systems make use of some form of protected cropping structure whether that is a simple rain cover, shade house or a high-technology greenhouse; however, in milder climates systems may be set up outdoors (Fig. 2.8). In the early days of hydroponics, many systems, some quite large in scale, were set up directly outdoors and produced significant quantities of fresh fruit and vegetables. In the early 1940s the Gericke system of production was used for large-scale vegetable production on the rocky Pacific Islands with the objective of supplying US Navy troops during the Second World War (Rumpel and Kaniszewaki, 1998). Other extensive outdoor systems largely producing mostly small vegetables were set up in many other countries from the mid-1940s onwards. It was the development of plasticulture and high-technology greenhouse structures that largely saw commercial hydroponics being confined to protected cropping. More recently a growing interest in using soilless culture for the production of some fruits and vegetables in the open field has developed (Rumpel and Kaniszewski, 1998; Hochmuth *et al*., 2008; van Os *et al*., 2012).

The main disadvantage of outdoor production is that rainfall can not only dilute the nutrient solution but also regularly wet the foliage, leading to an increased risk of fungal and bacterial disease. Outdoor hydroponic production can take many forms, the most common being drip-irrigated substrate systems and NFT channels for small crops such as lettuce mounted on benches above the ground. Many smaller, hobby or backyard, urban or rooftop-type hydroponic and aquaponic systems may start out as outdoor production units and gradually add a degree of protected cultivation such as an open roof structure as costs allow. Despite being positioned outdoors, many systems use some form of environmental modification such as natural or artificial shelter belts to control

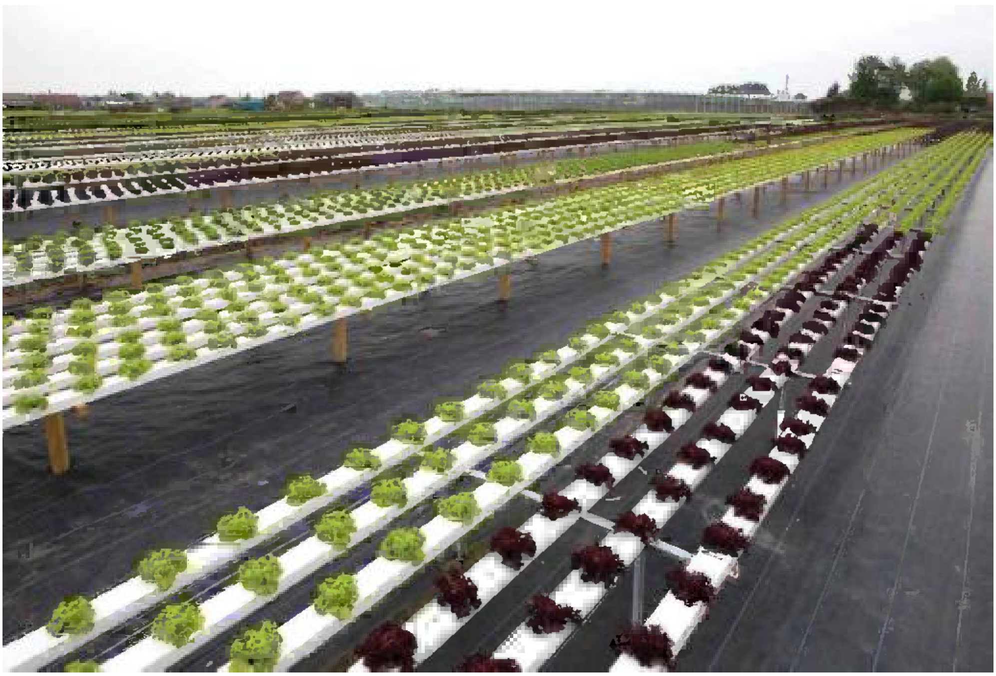

Fig. 2.8. An outdoor NFT lettuce production system.

winds and create a warmer microclimate, row covers placed directly on top of plants in frost-prone areas or plastic cloches over small plants such as lettuce and herbs.

Commercially, outdoor hydroponic production has not undergone the same degree of research as protected cropping systems; however, as a low-cost alternative, outdoor production has potential in a number of situations and for specific crops. The use of soilless culture methods in the open field has also been seen as a viable alternative where factors such as soil sterilization, limited water resources and issues with soil quality or contamination have arisen. Strawberry growers in North Florida, which has a mild winter climate, utilize outdoor soilless bag culture systems for out-of-season berry production. Soilless cropping outdoors provides an opportunity for many small producers to intensively produce strawberry outdoors without the investment required for extensive soil fumigation and mulching of soil production beds as well as extensive crop rotational programmes (Hochmuth *et al*., 2008). Since the withdrawal of the soil fumigant methyl bromide, control of soilborne diseases, weeds and nematodes has become an issue with field-based strawberry systems. Under this outdoor hydroponic system, strawberry plants receive some protection via polypropylene frost row covers as is typically used in field-based crops. Outdoor hydroponic strawberry crops, with use of nursery-raised plug plants instead of the traditional bare-rooted runner planting stock, establish faster and decrease the time to first harvest (Hochmuth *et al*., 1998). In a study by Hochmuth *et al*. (2008), it was found that an outdoor lay-flat bag culture system produced approximately twice the yields of the same cultivars grown in traditional field production systems.

A further benefit is that the same land can be used for hydroponic strawberry production year after year without the need for rotational programmes to control soil diseases and other issues. The growing medium can be replaced as required, preventing carryover of disease pathogens; however, Hochmuth *et al*. (2008) reported that it is possible to grow a second crop of a different species such as leafy vegetables in the same bag after the initial strawberry plants have been removed. The advantage of hydroponic cropping is that any outdoor vegetables grown via this method are free of any sand or grit compared with those grown directly in the field. While outdoor hydroponic cropping of high-value crops such as strawberries produced higher yields than soil-based systems, with the advantage of cost savings, challenges such as keeping irrigation systems clean and free from clogging and protecting polyethylene bags from premature degradation from intense UV exposure need to be considered during system design (Hochmuth *et al*., 2008). In another study with outdoor-grown hydroponic tomato and pepper crops, the design of the irrigation system was also seen as one the greatest challenges to outdoor cropping. This was largely due to the use of drip tape and emitters which needed to be positioned correctly, with a sufficient leaching rate of 15–20% and flushing of the irrigation system to remove solid particles and organic matter from the system (Hochmuth *et al*., 2002).

Outdoor hydroponic systems for other commercial crops include leafy vegetables and herbs, fruiting vegetables such as tomatoes, cucumbers, melons and capsicum. In the Netherlands restrictions on the emissions of nutrients and pesticides to surface and ground waters and the delivery of uniform high-quality products to retailers have restricted some open-field vegetable production systems (van Os *et al*., 2012). Outdoor soilless production systems where nutrient solutions are contained or collected (i.e. closed systems) are seen as one way of conforming to new environmental standards for the protection of water quality by preventing leaching of nutrients and reducing soil and water pollution. The increasing interest in open-field hydroponic production has largely been led by new regulations regarding the protection of water resources in areas of intensive agriculture (Rumpel and Kaniszewski, 1998). Germany has also introduced regulations which severely restrict the use of fertilizers, plant protection compounds and irrigation in protected zones and growers must develop new technologies to address these problems. Studies on the use of open-field hydroponic systems have consistently proven that growth, yields and quality of plants are generally higher than those from conventional soil-based culture (Rumpel and Kaniszewski, 1998). Van Os *et al*. (2012) examined a system for outdoor production of hydroponic leek which has strict market requirements for stem length and thickness and found that high-quality, clean product without soil contamination and with a strong reduction in labour needed for market preparation could be produced. Results of this trial found that a fast-growing crop with 4 crops/year and at least 80 plants/m^2 were achievable with a much shorter production time than growing in soil (van Os *et al*., 2012). In a trial with outdoor-grown hydroponic tomato and pepper it was found that use of a perlite lay-flat bag system, irrigated with nutrient solution, produced higher yields than that from a standard, mulched, drip-irrigated production system (Hochmuth *et al*., 2002). This system was also used to produce several crops continuously with the perlite bags, with winter squash and cucumber successfully grown in the same media following tomato and peppers; the yields of these second crops were also greater than those of the same vegetables grown in soil-based systems (Hochmuth *et al*., 2002).

In milder climates, outdoor NFT and other solution culture systems are used for the commercial production of a number of crops, mostly lettuce, leafy greens, herbs and other vegetables. Many of these systems incorporate a standard NFT system with benches consisting of several adjacent channels positioned at a convenient working height. These open-air benches usually have the option of a small cloche placed directly over the channels clad in either plastic or shade cloth which provides protection from rain or excess light as required. The side of these cloches allows the cladding film or material to be slid up during the day for ventilation and to access the plants. Large-scale outdoor NFT operations typically have a central pump house containing a nutrient tank and dosing equipment from which the nutrient flows out and around the system, returning through a series of channels.

2.15 Controlled-Environment Agriculture

While the majority of protected cropping structures are clad in films and materials which transmit natural light for crop growth, in some regions protected cropping takes place indoors using only artificial lighting as the sole source of radiation for photosynthesis. An inhospitable outdoor climate can make use of greenhouses or other outdoor systems impractical, uneconomical or even impossible. A lack of natural light, very short day lengths, snow, ice and extremes of heat and/or cold can all make indoor cropping more economical in some regions than use of a greenhouse or tunnel structure. Indoor cropping systems may be set up in large, industrial-scale warehouses, in purpose-built facilities, educational and research laboratories, in urban areas where greenhouses are not practical, and even outside the Earth's atmosphere where NASA has grown fresh produce for astronauts onboard space missions (Stutte, 2006). Practically any building where there is sufficient ventilation, water, drainage and electricity to run the necessary equipment for crop production can potentially be used for plant cultivation. Commercial indoor protected cropping is most often carried out for high-value crops such as salad greens, herbs and potted plants which may be grown vertically or in 'tiers', many levels high, to utilize restricted indoor space more efficiently (see Chapter 12, this volume).

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