Greenhouse Operation and Management in Egypt

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Abstract One of the major advantages of producing vegetable crops and ornamental crops under protected cultivation around the world is the ability to produce high yields throughout the year regardless of ambient weather conditions. To accomplish this objective, climatic variables inside greenhouses (such as air and soil temperatures as well as carbon dioxide concentration) should be controlled. The greenhouse sector in Egypt has achieved many success stories related to improvement of food security for Egyptian people via providing the local market during winter season with an adequate quantities of vegetable crops and ornamental plants. However, exports of greenhouses products to the foreign markets are not sufficient until now; there are some constraints such as the adoption of modern technology for greenhouse climate control and the need to further develop these, as well as implementation of food safety legislation during the different production steps.

As production costs increase by using such practices, growing areas in protected cultivation are trending in mild climatic regions of the world, where plants can grow without using artificial control of the greenhouse environment. There are several constraints related to greenhouse irrigation management such as misuse of water resources causing serious yield reductions; low irrigation efficiency can be primarily attributed to poor management of irrigation water in addition to technical problems

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of on-farm irrigation applications, as well as inadequate maintenance of irrigation systems often resulting from inadequate management in operation and maintenance. The use of greenhouse and plastic house techniques has contributed to better water-use efficiency.

The plastic or glass cover creates a modified microclimate in which radiation and wind movement are lower but relative air relative humidity is higher under greenhouses than in the open field, favoring a reduction in evapotranspiration. Furthermore, the higher temperature results in increased crop growth rate and higher obtained yield per unit area of protected cultivated land. Protected cultivation is a proper technology for improving vegetable crops productivity.

This chapter illustrates several beneficial agricultural practices in terms of the greenhouse sector. Work in the greenhouse sector considers greenhouse management and the proper tools that can be used depending on many factors such as the crop type, targeted market, technician availability, head and operation costs, etc.

The scientific background about greenhouse management will be explained in this chapter with the details necessary to provide the background needed about the scientific base of the modern technology. This chapter also took into consideration information needed for the local small farmers who use simple greenhouse technology to give information to inform critical management points such as proper cover materials and greenhouse ventilation systems. Furthermore management of food safety for greenhouses products and how to reduce the use of chemical pesticides through fertilization management are vital.

Recently, Egypt has established a national mega project for the establishment of 100,000 acres of greenhouses during the next few years. This project needs a lot of infrastructure, materials, manufacturing, and labor and technicians. Management of 100,000 acres of greenhouses will need proper qualified advisors and properly trained staff. There are a limited number of advisors and proper technician in Egypt because many good advisors and technicians left to work for in Gulf countries due to better salaries provided. There is an urgent need to prepare a new generation of advisors and technician in a short amount of time. The current chapter is a technical guideline for the greenhouse sector and can be used as a reference for those who work in the protected agricultural field.

Keywords Agriculture, Egypt, Food safety, Greenhouse, Irrigation, Management, Mega project, Pesticide, Technology

Contents

1 Introduction

As a result of agricultural land urbanization, rapid population growth, and insufficient product quantity and quality, a contingency plan must be developed as soon as possible to increase the productivity. These contingency plans should include adopting state of the art, modern technology in agricultural production and extending greenhouse areas. Then, protected cultivation emerged as a way to protect crops from adverse weather conditions allowing production year-round and the application of an integrated crop production and protection management approach for better control over pests and diseases.

Today’s greenhouse technologies mean it is possible to commercially cultivate all horticultural crops and species in any region of the world, provided that the greenhouse is properly designed and equipped to control the climatic parameters. Greenhouse design and location must optimize the climatic factors to be suitable for the cultivating crops.

In the eighteenth century, Egypt started commercial production of protected agriculture for vegetables and ornamental plants. During this period, there was significant progress in the following aspects: (1) greenhouse design, (2) use of low tunnels, (3) type and quality of the plastic covering material, (4) fertigation, (5) polyethylene mulch, (6) use of high-yielding hybrids and cultivars, (7) plant training and pruning techniques, (8) integrated pest management, (9) use of pollinator insects, (10) climate control, and (11) soil solarization.

Greenhouse production helps to meet the local market needs from the vegetables and ornamental plants. Besides supplying the local markets, the production of greenhouse should be greatly valued for its export potential to play an important role in the foreign trade balance of several national economies in Egypt. However, the intensification of greenhouse crop production has created favorable conditions for many devastating pests and diseases. This has significantly increased the need for pesticide applications. At the same time, legislative measures and standard requirements regarding the food safety of vegetables have become increasingly demanding. Food safety issues are the main barriers of export of produce to European Union countries according to the GLOBALGAP legislations.

Over the last two decades, use of solar agricultural greenhouses has globally increased especially in developed countries. The primary objective of a greenhouse is to produce high yield and good-quality yields during the non-cultivation season, which is possible by providing and maintaining an optimal level of light intensity, air temperature, and relative humidity at every stage of the crop growth. An appropriate air conditioning including heating and cooling systems can be equipped with the greenhouse for this purpose. These, as a result, will have significant impacts on the cultivation time, quantity, and quality of the products.

The greenhouse climate with the optimum range in terms of light, temperature, ventilation, and moisture directly affects the success of the production. Among these factors, the temperature is one of the most important climatic factors that should be managed inside the greenhouse. The vital (physiological and biological) activities of the plants usually slow down at 10°C and cease at 7°C. Providing appropriate air temperature and relative humidity in the greenhouse help to decrease diseases, infections, and use of chemical pesticides. Thus, the problem of pesticide residue on crops is alleviated and high-quality products are obtained.

Heating of greenhouse is essential and required for an efficient and reliable production especially during the winter season in Egypt. Regarding the greenhouses heating, renewable energy sources should be adopted instead of fossil fuel heat energy sources. Solar energy is an important alternative heat energy source and is a significant opportunity in Egypt.

The most commonly grown species in greenhouses are vegetables with medium thermal requirements (tomato, pepper, cucumber, melon, watermelon, green bean, eggplant, etc.). The aim is to extend the growing calendars beyond the conventional open-air cultivation season, and thus increase profitability. Nowadays, the production of greenhouse crops in geographical areas without suitable climate conditions is highly questionable since it entails significant and expensive artificial climate control.

The technology for vegetable enterprise development in Egypt produced a set of tools and standard operation practices for farmers, technicians, and extension specialists, highlighting the advantages of water management, salinity, and product quality of the greenhouse systems compared with traditional cultivation practices for export and domestic markets.

The overall objective is to restore small-scale farmers' capability to produce high-quality and safe vegetables under protected cultivation. The objectives of the agriculture strategy in Egypt are to increase productivity per unit of land and water through more efficient use of limited resources, as well as reduce the cost of production unit and thereby increase in the national output and farmers' incomes.

2 Planning and Design of Greenhouse

Greenhouse cultivation has a special place in agricultural production. In addition to the traditional greenhouse production, there has been an increase in the number of the modern greenhouse structures that allows environmental control in Egypt in recent years.

A greenhouse has one purpose: to provide and maintain an optimal level of microclimatic conditions that will result in optimum crop production or maximum profit. This also includes an environment for work efficiency as well as for crop growth, development, and productivity.

The factors affecting greenhouse management before investing are as follows:

1. Available marketing systems and the transportation
2. The climatic conditions (ambient air temperature, intensity of solar radiation, rainfall, air relative humidity, wind speed, and prevailing wind direction)
3. The fuel and power availability (gas, oil, coal, or renewable energy sources)
4. The water availability and its quality (a good source of high quality is cheap, while a poor water supply will limit growth and may require additional investment for purification)
5. The kind of available soil and its drainage characteristics

The natural radiation conditions are the main limiting factor to consider when establishing greenhouses. Therefore, the natural radiation conditions make it necessary to design and locate greenhouses to optimize the interception of solar radiation during the autumn and winter months.

Protected cultivation in greenhouses causes the increase of daytime temperature (compared to the outside temperature) to very high values depending on: characteristics of the cladding material, outside wind velocity, and incident solar radiation and transpiration of the crop grown inside the greenhouse.

2.1 Greenhouse Site Selection

Site selection is a key factor for profitable and sustainable greenhouse production. The main factors determining location and site selection of a greenhouse production area are: cost of production unit, quality of produced yield, and transportation cost to markets [1, 2]. Obviously, cost and quality of production depend on the local climate and the greenhouse growing conditions.

The specific selection of a greenhouse location must take into account a variety of factors [2]:

1. Topography: ground slope for drainage, flat in width direction, main axes slope of 0–0.5% (never >1–2%, which would need terracing), and building orientation (a south-facing slope is good for winter light and protection from northerly winds).

2. Microclimate: not frequently fogged areas, windbreaks, air pollution especially near cities, avoid flooded areas, soil characteristics, and expansion for future greenhouse or auxiliary buildings.
3. Irrigation water: a dependable supply of high-quality water is needed for greenhouse operation.
4. Greenhouses need a dependable supply of energy in the form of electricity and fuel for heating, labor availability, and communications network.

2.2 Plan Layout

The individual greenhouse (single-range greenhouse) may be easily constructed. One disadvantage may be that individual greenhouse in total requires more heat per unit area of surface area than a multi-span greenhouse, because of the larger ratio of cover surface area to floor surface area. While the gutter-connected range (multi-span greenhouse) keeps all activities inside one building, a central heating system can easily serve all areas. It may not be as easy to expand or contract space use as with the individual greenhouse.

2.3 Local-Type Greenhouses (Wooden Greenhouses)

These greenhouse types are normally very low-cost structures with little climate control besides natural ventilation; they are built with local materials (i.e., wood) and covered with polyethylene plastic film. The parral-type greenhouse is probably the most widely used in terms of surface area.

The parral greenhouse is made of a vertical structure of rigid pillars (wood or steel) on which a double grid of wire is placed to attach the plastic film.

Local-type greenhouses require a relatively low level of investment, making them suitable for farms operated by small growers. However, there are significant design-associated problems, such as lack of good natural ventilation, as a result of:

- Low ventilation surface area, due to a poor combination of side and roof ventilation and to the construction of excessively small roof vents, resulting from the grower's fear of sudden strong winds that may damage the greenhouse.
- Inefficient ventilator designs – for roof ventilation, flap ventilation is always preferable to rolling ventilators as it provides higher ventilator rates (almost three times greater airflow according to [3].
- Use of low porosity insect screens – insect-proof screens strongly reduces the air exchange rate.

Good agricultural practices require good ventilation and higher light transmission especially during the winter season (main season of greenhouse production). The lack of good ventilation in most local-type greenhouses can be fixed by improved design of the ventilation systems. Light transmission depends on the properties of the covering material and the number of opaque supporting members, as well as the greenhouse geometry and orientation. In terms of roof slope, computer simulations show that during the winter, increasing the roof slope from 11 to 45° can increase daily light transmission by nearly 10%, since losses due to reflection are reduced. In practice, it is more useful to find a compromise between good light transmission and construction costs, and most new greenhouses have a roof slope of 25–30°C.

With regard to greenhouse orientation, there are two main factors that have to be balanced before choosing the best solution: light transmission and ventilation. Moreover, there is research related to produce tropical fruit from the wooden greenhouse covered with screen-proof insect net.

2.4 Utilities

2.4.1 Electric Power

An adequate electric power supply and distribution system should be provided to serve the environmental control and mechanization needs of the greenhouse.

2.4.2 Water

Plants require an adequate supply of moisture for optimum growth and sufficient productivity. Water is the medium by which plants absorb nutrient elements. A correctly designed watering system with adequate supply means adequate amount of water needed each day during the year. This amount will depend upon the area to be watered, kind of crop grown, and climatic conditions. Water absorbed by the root system moves through the roots into branches and leaves. Water vapor then transpires through stomata in the leaves into the atmosphere surrounding the plant.

It is very important to know the existing water quality before using it in the greenhouse. A common problem is that of a high salt content in the irrigation water. This frequently occurs along coastal areas, where the seawater may infiltrate the groundwater. Quantities of sodium bicarbonate or sodium chloride can become high enough to be injurious. Groundwater in the western and southwestern Egypt can contain excessive quantities of sodium and boron. A total soluble-salt reading (via electrical conductivity) gives a good assessment of this problem.

A common problem is high salt content in the irrigation water. When this is experienced, the water should be analyzed, and those specific elements making up the salts should be avoided or at least reduced in the fertilizer program, because the removal of salts is expensive. When high salt levels exist, the root zone should not be allowed to dry excessively, since that would concentrate the salts. Reverse osmosis systems have been used successfully by a few greenhouse firms. This is an added cost which renders the firm all the less competitive.

High boron is a problem in many arid, coastal regions. Boron availability to plants can be reduced by precipitating it in the root media with calcium. Adding calcium or raising the pH to the upper end of the safe range for a crop will lessen boron toxicity. Bicarbonate is particularly damaging to plants. It causes variable chlorosis over the plant, burning of leaf margins, and generally poor growth. Besides by reverse osmosis, bicarbonate can be removed by acidifying the water with such acids as sulfuric acid, nitric acid, or phosphoric acid. These may be injected into the irrigation water source. At the lower pH level desired for plant growth, much of the bicarbonate converts to carbon dioxide gas and water.

2.5 Growing Systems

There are four functions that the root medium must hold water and nutrient in a way that it is available to the plant and provide for the exchange of gases between roots and the atmosphere above the root medium. Field soil is composed of three mineral components as shown in Fig. 1.

Sand provides excellent support and gas exchange but has insufficient water and nutrient holding capacity. The coarse particles of sand have little surface area per unit of volume compared to the finer particles of clayey soil or peat moss. Since water is held on the surfaces of particles, sand has a small reserve. Plants grown in sand would need to be watered three or more times per day in the summer, since most nutrients in a sand medium are held in the water films.

Clay has a high nutrient and water-holding capacity and provides excellent plant support. The water films of adjacent particles come into close contact, leaving little open space for gas exchange. Carbon dioxide produced by the roots and by microorganisms cannot adequately leave the clay. In high concentration it suppresses respiration, which in turn slows growth. Oxygen, also needed to keep the processes

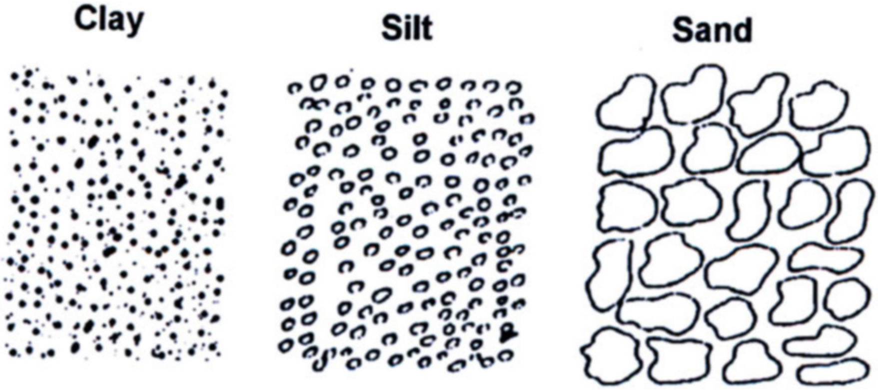

Fig. 1 Texture description of particle sizes for three different types of soil

of respiration going, cannot adequately diffuse into the clay. Consequently, clay is a poor medium for plant growth. The finest particles, clay, extend up to a maximum diameter of 2.0 μm. Clay feels sticky to touch.

Silt is floury and composed of particles up to 50 μm. Texture terms include sandy load, silt loam, and clay loam for soils predominating in sand, silt, and clay, respectively. Loam refers to a reasonable balance of all three materials.

2.5.1 Hydroponics System

Hydroponics is a production method by which plants are grown in a nutrient solution rather than in soil. It used as a root medium but lacks gas exchange and plant support.

Advantages of hydroponics system can be concluded as follows: greater plant density, higher yields and better quality, less water consumption, and less disease and fewer insects. The disadvantages of hydroponics system are as follows: increased initial investment (specific pumps, tanks, control systems, and support systems increase the costs per square meter), higher energy costs (specific pumps, specific heat-distributing system, lights, and additional control system), and more technical skills needed. Several soilless growing systems are illustrated in Fig. 2.

2.5.2 Sand/Stone Culture

Seedlings are set directly into this medium for growing almost any type of plant consists of a deep bed (45–60 cm) of sand, stone, or trap rock placed in a plastic-lined trough or bed which slopes to one point in order to drain off excess nutrient solution (a minimum slope of 2%).

2.5.3 Troughs and Pipes

Open and closed troughs and pipes may contain just the nutrient solution or may be filled with peat moss. PVC pipes has a diameter of 5–7.6 cm with holes each has a diameter of 15 cm on centre. They are used for leaf lettuce production. This system is a suitable for small canopy plants such as strawberry, tomatoes, cucumbers and lettuce.

2.5.4 Bags

A modified hydroponics system uses polyethylene film bags, filled with a peat moss-vermiculite mix or foam, placed end-to-end. Drip tubes supply the nutrient solution into the bags system.

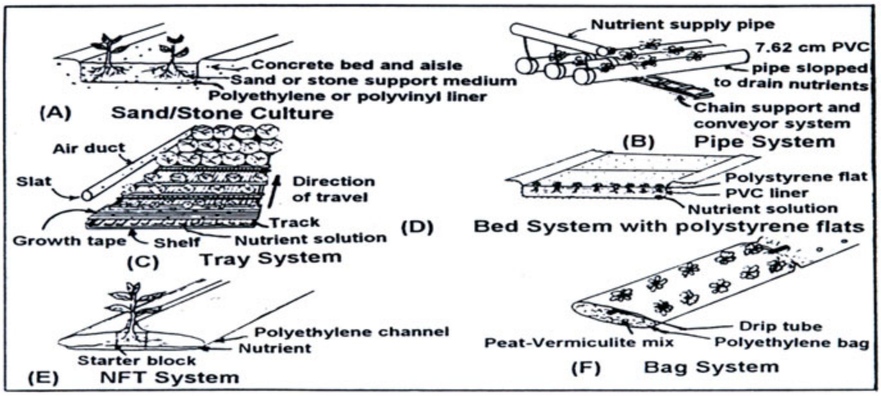

Fig. 2 Major soilless growing systems used in Egypt (**a**) Sand/Stone culture, (**b**) Pipe system, (**c**) Tray system, (**d**) Bed system with polystyrene flats, (**e**) NFT system, (**f**) Bag system

2.5.5 Nutrient Film Technique Solution (NFT)

This NFT system used in Egypt is formed by thin plastic channels film or PVC gullies, plastic channels film has two faces color (one face is white color and another is black) which are placed on the floor and slope the length width of the greenhouse. Nutrient solutions are supplied to one end of the channel through plastic tubing and collected into a below-ground reservoir at the other end by the gravity. Seedlings are usually grown in small pots, poly bags, or growth blocks in the channel. Also, aeroponic-modified system plants are supported through a plastic cover to a closed tank. Nutrient elements are supplied to the root system as a fine mist or fog.

Besides the plant support system, tanks, pumps, and control systems are needed. Tanks of concrete, plastic, or iron coated with epoxy are commonly used. Submersible pumps made for chemical solution should be used because fertilizer salts corrode pumps made for use with freshwater. Control systems can be as simple as a timer, manual switches, or complex computers which automatically adjust the chemical content of the nutrient solution.

3 Greenhouse Climate Control and Energy Use

All greenhouse cultivation systems comprise fundamental climate control components; depending on their design and complexity, they provide more or less climate control and condition to a varying degree plant growth and productivity from the land unit.

The provided tools could control air temperature, light intensity, and air relative humidity inside the greenhouses. It conditions not only crop growth and yield but also energy needs, which can account for up to 40% of the total production costs.

A greenhouse is constructed and operated to provide an acceptable plant environment that will contribute to a profitable enterprise. Photosynthesis is the process by which light energy in the range of 0.39–0.70 μm wavelength interval is converted into usable chemical energy by green plants. It is a process by which carbon dioxide (CO_2) and water (H_2O), in the presence of light and chlorophyll, are converted into carbohydrates and oxygen.

The carbohydrates can be moved from the green stem and leaf cells where photosynthesis occurs to all other parts of the plant. Amino acids may be formed and then combined into chains called protein. Fats maybe formed carbohydrates from all these compounds, yet other compounds arise such as cellulose for cell walls, pectin to cement the walls together, hormones to regulate growth, and DNA to constitute chromosomes. These processes result in the growth of the plant which can be detected as an increase in dry matter.

Respiration is the reverse process of photosynthesis, by which carbohydrates and fats are broken down, and carbon dioxide, water, and energy are released as follows:

$$\text{Carbohydrates} + \text{Oxygen} \rightarrow \text{CarbonDioxide} + \text{Water} + \text{Energy} \qquad (1)$$

The respiration process occurs in all living organisms at all times. True photosynthesis depends on air temperature surrounding the pants, light intensity, water, and nutrient elements availability. Energy must be liberated at times to power other processes in the plant. When photosynthesis exceeds respiration, net growth occurs. When they equal each other, net growth stops, and if respiration exceeds photosynthesis, the plant declines vigor and will eventually die. To ensure that photosynthesis exceeds respiration, plants are grown cool at night to keep the respiration rate down and warmer by day to enhance photosynthesis.

3.1 Environmental Parameters Affecting Growth of Protected Cropping

There are eight main parameters that affect growth under greenhouse conditions: light, air temperature, air relative humidity, vapor pressure deficit, carbon dioxide concentration, air speed, root environment, and pollutants.

3.1.1 Light

Visible light (0.39–0.70 μm) provides essential energy for plant development and growth. Intensity, duration, spectral distribution, and quality of light affect plant response. The effect of radiation can be conveniently divided into three parts: (1) effect on flowering, (2) effect on photosynthesis, and (3) effect on plant temperature and water loss. Photosynthesis and water loss are usually considered as being influenced by high intensity. Flowering, however, can be determined by illumination levels less than 0.044 W/m^2. Ultraviolet light (0.29–0.39 μm) is generally detrimental to plants. Photosynthesis proceeds only with visible light, of which the red and blue wavelengths are used most efficiently.

The change from vegetative to product development in many plants is controlled by red light (0.66 μm) and far-red light (0.73 μm). Light intensity is the most critical variable influencing photosynthesis process. Flower crops can be classified as sun or shade plants. Sun plants can be grown in full sunlight with no adverse effects, while shade plants are injured if exposed to light intensity above a specific level. The single leaf reaches its maximum rate of photosynthesis at 131.2 W/m^2. An intensity of 438.6 W/m^2 might be required for the whole plant in order to raise the light intensity within the leaf canopy to 131.2 W/m^2.

When the daily total solar radiation drops below 100 W/m^2, supplemental illumination may be useful. At 500 ppm carbon dioxide, individual leaf photosynthesis reached a maximum near 139 W/m^2. Plants which respond to relative length of day and night are termed photoperiodic. Photoperiodic affects flowering and is generally independent of light intensity. Plants can be grouped as long day, or day neutral, with the length of darkness being more important than the length of the light period.

Not all light is used in the photosynthesis process as light is classified according to the wavelength (μm). This classification is referred to as quality of light; as an example, ultraviolet light (UV) has short wavelengths below 0.4 μm, while blue, green, yellow, orange, and red light occur around wavelengths of 0.46, 0.51, 0.57, 0.61, and 0.65 μm, respectively. Far-red light (0.70–0.75 μm) occurs at the limit of our visual perception and has an influence on plants other than through photosynthesis. Infrared energy occurs at longer wavelengths and is not involved in plant processes.

It is primarily the visible spectrum of light that is used in photosynthesis. There are peaks in the blue and red bands where photosynthetic activity is higher. When blue light alone is supplied to plants, growth is shortened, hard, and dark in color. When grown in red light, growth is soft, and internodes are long resulting in tall plants. All visible light qualities (wavelengths) are readily utilized in photosynthesis.

3.1.2 Air Temperature

The majority of plants grown in greenhouses are warm-season species, adapted to average temperatures in the range 17–28°C, with approximate lower and upper limits of 12 and 32°C [4]. If the average minimum temperature outside greenhouse is less than 10°C, the greenhouse is likely to require operate heating, particularly at night. When the average maximum outside temperature is less than 27°C, then ventilation will prevent excessive greenhouse temperatures during the day; however, if the average maximum temperature is greater than 27–28°C, artificial cooling may be necessary. The maximum greenhouse temperature should not exceed 30–35°C for prolonged periods for most growing crops.

All plants have an air temperature range in which they can be grown. All biochemical reactions in the plant are controlled by enzymes that are heat sensitive. These all have the net effect of building carbohydrates and storing energy. Plant temperature is affected by radiation energy transfer, convective heat transfer, and evaporation from plant surface. The relationship between plant growth and the temperature is complex because it is a factor in the reaction rates of various metabolic processes. Greenhouse crops are grown at specified night air temperatures with a daylight minimum increase of from 4 to 6°C.

As the indoor air temperature is increased above 30°C during the summer season, the green leaves and stem length are thus reduced making the rate of vegetative growth at a minimum level. Also, excessive air temperature of greenhouse causes damping-off, loss of stem strength, delay flowering, decreased vitality and insemination of seeds, loss of fruit set, loss of fruit size, and increased possibilities of infection by pathogenic organisms. Reversely, as the indoor air temperature of the greenhouse is decreased lower than 15°C, the percentage of flowerage and vitality of insemination seeds are decreased making the fruit set at a minimum level.

Heat energy can be reflected, transmitted, absorbed, conducted, reradiated, or used to evaporate water. The latter generally requires over 2,093.4 J/g of water evaporated. Obviously, if radiant energy is absorbed, plant temperature must rise until equilibrium is reached at some higher value. The new temperature equilibrium is determined by the following facts:

1. The fact that plants will radiate thermal energy to their surroundings, the amount depending upon the temperature differential between plant, and the surrounding area (greenhouse roof, heat pipes, etc.).
2. The removal of energy by conduction and convection processes or the flow of cooler air stream over warm leaves of the plant. As air movement increases, more heat is conducted away, and plant temperature comes closer to the indoor air temperature. If the indoor air temperature is higher than the plant temperature, heat can flow in the opposite direction, tending to raise plant temperature.
3. The amount of energy used in photosynthesis is so small. It could be commonly ignored in assessing heat energy balance of growing crops.
4. The evaporative rate of the plant. As a rule, between 70 and 90% of absorbed solar radiation is utilized to evaporate water from the plant. Recent research work revealed that between 48 and 52% of solar radiation available inside the greenhouse is utilized to evaporate water from the plant.
5. The final equilibrium temperature is influenced by the capacity of the plant to store heat energy or thermal heat capacity of the tissue and its mass. Therefore, temperatures of thin leaves will vary faster and farther than thick leaves, or large masses such as flower buds or storage organs, when there is a change in the environment.

In order to investigate the variables determining air temperature inside the greenhouse and calculate the necessary measurements for control air temperature, a simplified model of the greenhouse energy balance is formulated [5]. Equation simplifies the greenhouse energy balance to

$$V_{\mathrm{a}} = \frac{0.0003\tau R_{\mathrm{s,\,o\text{-}max}}}{\Delta T} \tag{2}$$

where, V_{a} is the ratio Q/A_{g}, Q is the ventilation flow rate (m^3 [air]/s), A_{g} is the greenhouse ground surface area (m^2), τ is the greenhouse transmission coefficient to solar radiation, $R_{\mathrm{s,\ o\text{-}max}}$ is the maximum outside solar radiation (W/m^2), ΔT is the temperature difference between a greenhouse and outside air (°C).

4 Temperature Control

4.1 Wind-Dependent Heating

In Spite Of a1°C reduction gives an energy saving of around 10%, low temperature reduces plant growth rate and development of most crops and may significantly reduce crop quality. Thus a lower heating air temperature will save energy but is generally not feasible economically as it results in affected crop production which is not always compensated for by the lower energy costs. A more economic measurement of reduced heating greenhouse air temperatures is wind-dependent air temperature control. Heat losses are increasing linearly with increasing wind speed. Therefore, energy can be conserved by reducing the heating set points when it is windy and compensating for these using increased temperatures at low wind speeds. This method results in energy savings of 5–10%.

Temperature Integration Another option for energy efficient for control air temperature is the so-called temperature integration (TI) method. This method is based on the fact that the effect of greenhouse air temperature on plants growth and production depends on the 24-h average greenhouse air temperature rather than distinct day/night greenhouse air temperatures [6]. However, there are limits to this approach, and plants have to be grown within the sub- and supraoptimal temperatures to prevent reduced quality and/or production levels due to poor fruit or flower development.

In general, application of temperature integration leads to higher greenhouse air temperature during daytime and lower air temperatures at night. However, the approach of using sufficient ventilation set points can also be combined with the use of lower day heating set points and then higher temperatures under thermal screens at night. The advantage is to fully exploit solar heat gain at day and when additional heat is required, to add it preferably at night when heat losses from greenhouse are limited due to the closed thermal screen. There are potential energy savings of up to 20% [7]. However, when setting bandwidths for temperature integration, a balance must be found between maximizing energy savings and minimizing detrimental effects on yield or quality. The balance varies enormously depending on the crop, so specific crop knowledge is required.

4.1.1 Air Relative Humidity

The second important variable is relative humidity. Air relative humidity is the ratio of the actual vapor pressure of water vapor in the air to the vapor pressure that would be present if the air was saturated with moisture at the same temperature. Water vapor moves from one location to another because of vapor pressure differences, so air relative humidity affects transpiration from plants by affecting the vapor pressure difference between a plant leaf and surrounding air. Relative humidity within the range of 60–90% has little effect on plants. Values below 60% may occur during ventilation in arid climates, or when plants are young with small leaves, and this can cause water stress. Serious problems can occur if relative humidity exceeds 95% for long periods, particularly at night as this favors the rapid development of fungus diseases such as *Botrytis cinerea*.

Normal plant growth inside the greenhouse generally occurs at air relative humidity between 35 and 80%. A secondary effect is the response of pathogenic organisms. The third effect is the influence on indoor vapor pressure deficit.

4.2 Humidity Control

An airtight greenhouse will have reduced air exchange and higher air relative humidity. Thermal blankets or double glazing layers will also result in an increase of the air relative humidity. Reduced air exchange will reduce the water vapor removed from the greenhouse. Additional insulation will result in higher inside surface temperatures, reducing the condensation potential. The condensation rate depends on the rate of air movement across the surface, the rate at which heat of condensation is removed from the surface, and the rate of evaporation from other surfaces in the greenhouse. Water vapor of indoor air condenses in a film on fenestration surfaces that are at a temperature below the dew-point temperature of the indoor air.

A major fraction of the heat transfer from the greenhouse to the outside environment is by natural ventilation. Under low radiation condition and moderate ambient temperature, natural ventilation is generally used to prevent high relative humidity inside the greenhouses. Consequently, a substantial fraction (5–20%) of the total energy consumption is related to control relative humidity. Although high relative humidity is generally associated with increased hazard of fungal diseases and reduced product quality (e.g., *Botrytis*, blossom end rot), it may also be a positive effect for crop yield and quality [8]. Reducing the level of air relative humidity is costly as a result of the energy consumed and should be assessed against the added value of the crop price. An increase in the air relative humidity set point of 5% decreases the energy consumption by approximately 6%. To reduce “humidity control related” energy consumption, there are several options: higher humidity set points, reduction of the transpiration level of the crop, and active dehumidification with heat recovery.

In general, the indoor air relative humidity of the greenhouses will be controlled by the temperature of coldest inside surface. The simplest method for air relative humidity control in cool or cold weather is to bring in outdoor air, heat it, and allow it to absorb moisture before exhausting it to outside the greenhouse. A greenhouse filled with mature pot plants may lose up to about 0.75 kg of water vapor per square meter of greenhouse floor surface area per hour during the daylight time; loss at nighttime will be less. If evaporated moisture is not removed, indoor air relative humidity of the greenhouse will increase until the air is saturated or till condensation begins on a cold surface.

Horizontal airflow in the greenhouse will help alleviate the problem by moving air across plant surfaces to keep them dry. Moving air also increases mixing and prevents temperature stratification in the greenhouse.

Thermal Screens Energy-efficient thermal screen control involves achieving a balance between the yield and quality effects related to greenhouse air relative humidity, light intensity, and energy saving. Energy-efficient (humidity) screen control can be achieved by opening the screen prior to the ventilators to maintain a given air relative humidity set point. When closing the screen at night, an additional operational energy saving (4%) can be obtained without any yield losses. If the opening of the thermal screen is delayed until radiation level outside greenhouses becomes 50–150 W m^2, the heat exchange of the greenhouse is thereby reduced for a longer period during the early morning hours [9].

A thermal screen adds an additional barrier between the greenhouse climate conditions and its surroundings and reduces both convection and ventilation loss. Thermal screens can be either fixed or movable. Install fixed thermal screens are normally used during both the early plant growth stage and production stage of the crop. But, both the constant reduction of the light level and the increased air relative humidity limit the period of application. Consequently the potential operational energy saving is achieved. Movable screens have less impact on light transmission than fixed screens or double covering materials. Using thermal screen could reduce energy consumption by more than 35–40%, depending on the material. In practice, movable screens are closed for only part of the entire 24-h period depending on the grower's criteria for opening and closing, which are generally related to humidity and light levels.

Covering Materials and Screens Most energy loss in naturally ventilated greenhouses occurs through convection and radiation from the greenhouse cover and sensible and latent heat transfer through ventilation. Improved insulation and reduced ventilation are therefore the first steps toward creating energy-conserving greenhouses. The basis of energy reduction is a good maintenance of greenhouse hardware (doors, cover, sidewalls, and foundation). Procedures must be taken to prevent unnecessary air leakage from the greenhouse to outside environment: keeping greenhouse's doors closed, sealing air leakages, repair of broken greenhouse cover material and sidewalls, and uniform closure of greenhouse natural ventilators.

Increasing the insulation value of the greenhouse has a major impact on energy use as most energy loss takes place through the greenhouse cover. Therefore different technologies are applied, including an increase of the insulation value using a double or triple layer of cover materials and application of coatings to reduce heat loss [10]. However, a major disadvantage of most insulating materials is the reduction in solar radiation transmission and increased air relative humidity inside the greenhouses. In practice, the potential energy saving of double and triple greenhouse covering materials is rarely achieved, since the grower will try to compensate for the higher air relative humidity levels by increasing the dehumidification of the greenhouse climate [11].

Reduction of Transpiration Reduction of transpiration may have positive effects on energy efficiency since lower transpiring crops bring less water into the air and therefore require less energy for humidity control under low irradiation conditions. Higher CO_2 levels, by decreasing stomatal conductance and thus transpiration, may also improve energy efficiency by 5–10% without affecting photosynthesis or growth. Controlled reduction of the leaf area for crops with a high leaf area index, such as pepper, may reduce energy use without any impact on production. Halving the leaf area by removing old leaves in tomatoes resulted in a 30% reduction in transpiration with no detrimental effect on crop yields [12].

4.2.1 Vapor Pressure Deficit (VPD)

Vapor pressure deficit (VPD) is a valuable way to measure the greenhouse microclimate conditions and consequence the effectiveness of environmental control system. VPD can be used to evaluate the disease threat, condensation potential, and irrigation needs of a greenhouse crop. An important step toward disease management is to prevent conditions that promote disease. Condensation prevention is important since greenhouse pathogens often require a water film on the plant to develop and infect. The air is saturated when it reaches maximum water-holding capacity at a given temperature (dew point). Adding moisture to air beyond its holding capacity leads to deposition of liquid water somewhere in the system.

Air vapor pressure (VP_{air}) is a measurement of how much water vapor in the air, that is, how much water in the gas form is present in the air. More water vapor in the air means greater water vapor pressure. When the air reaches maximum water vapor content, the vapor pressure is called the saturation vapor pressure (VP_{sat}), which is directly related to air temperature. Thus, the differences between the saturation vapor pressure and the actual air vapor pressure ($VP_{sat} - VP_{air}$) is the mathematical definition of vapor pressure deficit (VPD). Higher vapor pressure deficit means that the air has a higher capacity to hold water, stimulating water vapor transfer (transpiration) into the air in this low humidity condition. Lower vapor pressure deficit, on the other hand, means the air is at or near saturation, so the air cannot accept moisture from a leaf in this high humidity conditions. The vapor pressure deficit (VPD_{air}) can be computed according to the following equations [13]:

$$\mathrm{VPD_{air}} = (1 - \mathrm{RH})P_{\mathrm{WS}}\ \mathrm{kPa} \tag{3}$$

where RH = indoor air relative humidity, decimal, P_{WS} = saturation vapor pressure at dry-bulb temperature, (kPa)

For dry-bulb temperature ranges from 0ºC to 200ºC, the saturation vapor pressure (P_{ws}) can be estimated from Eq. (4) [14]:

$$P_{\mathrm{WS}} = \exp(Z) \tag{4}$$

$$Z = \frac{C_1}{T} + C_2 + C_3T + C_4T^2 + C_5T^3 + C_6\ln(T) \tag{5}$$

where T is the dry-bulb temperature in Kelvin, and constants are as follows:

$$\begin{aligned} C_1 &= -5.8002206E+03 \\ C_2 &= 1.3914993E+00 \\ C_3 &= -4.8640239E-02 \\ C_4 &= 4.1764768E-05 \\ C_5 &= -1.4452093E-08 \\ C_6 &= 6.5459673E+00 \end{aligned}$$

Maintaining the VPD above a minimum value helps to ensure adequate transpiration and also reduces disease problems. During the day, humidity can usually be reduced using ventilation. However, at night, unless the greenhouse is heated, the internal and external temperatures may be similar; if the external humidity is high, reducing the greenhouse humidity is not easy. When the air vapor pressure deficit is too low, air relative humidity too high, and air temperature very low, the water may condense out of the air onto leaves, fruits, and other plant parts. Because the plants are unable to evaporate enough water to enable the transport of minerals (such as calcium) to grow plant cells, even though the stomata may be fully open, this can provide a medium for fungal growth and diseases. Therefore, a VPD target threshold can be used to influence ventilation and/or heating equipment used to increase the vapor pressure deficit by reducing the indoor air moisture level.

When the plants are unable to evaporate water, excessive turgor pressure within the cells can cause splitting and cracking of fruits such as green beans, cucumbers, sweet peppers, and tomatoes. When the vapor pressure deficit is too high (relative humidity is too low), the rate of transpiration from the plant leaves can exceed roots' water uptake. This in turn will cause the stomata to close and then photosynthesis to slow down. Once the stomata closed, the leaves are at risk of high-temperature injury since evaporative cooling is reduced due to the lack of water to transpiration. To avoid high-temperature injury and plant death from wilting, many plant species will curl their leaves or orient them downward in an attempt to expose less surface area to the sun. This can significantly downgrade the quality of potted and foliage plants and can also reduce the growth rate and quality of vegetable crops.

In high vapor pressure deficit (VPD) situations, it can use the current VPD reading to directly operate sprinklers, fog, or missing equipment to add water vapor to the indoor air while simultaneously cooling the indoor air through evaporation. Both of these effects will reduce VPD values and evaporation stress in the crop. Any consequential air temperature or relative humidity changes will be looked after by the standard temperature and humidity climate control strategies. A misting program based on VPD is capable of regulating the on time of the fog or mist nozzles to provide the maximum amount of water for evaporative cooling and VPD set-point control while minimizing plant and soil wetting.

In situations where the vapor pressure deficit (VPD) is too low, moisture must be removed from the indoor air, or the indoor air moisture holding capacity must be increased through a rise in temperature. Moisture removal can be accomplished by substituting the moist air with drier one (typically through ventilation). The need for this is normally established using air relative humidity measurements alone, and it is the standard practice for avoiding direct condensation onto greenhouse surfaces.

4.2.2 Concentration of Carbon Dioxide (CO_2)

Carbon is an essential plant nutrient and is present in the plant in greater quantity than any other nutrient. About 40% of the dry matter of plants is composed of carbon. Plants obtain carbon from carbon dioxide gas (CO_2) in the air. For the most part, CO_2 diffuses through the stomata opening in leaves when they are open. Once inside the leaf, CO_2 moves into cells, where, in the presence of light energy from the sun, it is used to make carbohydrates (sugars). The carbohydrates are translocated to various parts of the plant and transformed into other compounds needed for growth or maintenance of the plant. Air, on the average, contains about 0.03% CO_2.

The absorption rate of CO_2 depends upon several factors, including concentration, stage of growth, air temperature, and light intensity. All plants will respond to increases in CO_2 levels, but not all responses will be economically profitable. The combination of high CO_2 levels, elevated day air temperatures, and optimum light levels will reduce the time between germination and harvest by as much as 50% for some crops. CO_2 enrichment is essential to increase the quality of produce; indeed, a continuous or periodical increase of CO_2 inside the greenhouse may lead to an increase of over 20% in fruit production for both dry and fresh matter [15].

Inside an unenriched greenhouse, the carbon dioxide concentration reduces below the atmospheric level whenever the carbon dioxide consumption level by photosynthesis is greater than the supply rate through the greenhouse vents.

The poor efficiency of greenhouse ventilation systems in low-cost greenhouses coupled with the use of insect-proof nets produces relatively high carbon dioxide depletion (about 20% or more). Possible solutions are: increase the greenhouse ventilation rate through forced air; improve design and management of the existed ventilation system; or inject carbon dioxide inside greenhouses [16].

In the absence of injecting artificial supplies of carbon dioxide in the greenhouse environment, the carbon dioxide consumed during photosynthesis must ultimately come from the external environment through the ventilation openings. The concentration of carbon dioxide within the greenhouse must be lower than that outside in order to obtain inward flow. Since potential assimilation is heavily dependent on carbon dioxide concentration, plant assimilation is reduced, whatever the light level or plant status. The ventilation of the greenhouse implies a trade-off between ensuring inflow of carbon dioxide and maintaining an adequate temperature within the greenhouse, particularly during sunny days [17]. Stanghellini et al. [18] analyzed the cost, potential benefits, and consequences of bringing more carbon dioxide into the greenhouse: either through increased ventilation, at the cost of lowering temperature, or through artificial supply. They found that while the reduction in production caused by depletion is comparable to the reduction resulting from lower temperatures caused by ventilation to avoid depletion, compensating the effect of depletion is much cheaper than making up the loss by heating.

Optimal carbon dioxide enrichment depends on the margin between the increase in crop value and the cost of providing the carbon dioxide. Attempting to establish the optimal concentration by experiment is not feasible because the economic value of enrichment is not constant but varies with solar radiation through photosynthesis rate and with greenhouse ventilation rate through loss of carbon dioxide [19]. The optimal carbon dioxide set point depends on several factors: the effect of CO_2 on the photosynthetic assimilation rate, the partitioning to fruit and to vegetative structure, the distribution of photosynthate in subsequent harvests, and the price of fruit at those harvests, in addition to the amount of carbon dioxide used, greenhouse ventilation rate, and the price of carbon dioxide.

The emission of carbon dioxide depends on the total use and type of fossil fuel. For example, when coal is used, carbon dioxide emission is 80–100 kg/MJ; for diesel, 75 kg/MJ; and for propane, 65 kg/MJ, while for natural gas it is about 58 kg/MJ. The principal source of carbon dioxide enrichment in the greenhouse used to be pure gas; nowadays more frequent use is made of the combustion gases from a hydrocarbon fuel, for example, low sulfur paraffin, propane, and butane or natural gas, and more recently also from biogas. In these cases, attention should be given to monitoring the SO_2, SO_3, and NO_x levels, which can damage the crops even at very low concentrations.

4.2.3 Dehumidification

Water condensation refers to the formation of drops of water onto greenhouse walls from water vapor. Condensation of water drop occurs when warm and moist air in a greenhouse comes into contact with a cold surface such as glass, fiberglass, plastic, or structural members. The air in contact with the cold surface is cooled to the surface temperature. If the greenhouse's wall surface temperature is below the dew-point temperature of the air, the vapor in the air will condense onto the walls. Condensation always occurs in greenhouses from sunset to several hours after sunrise. During daylight hours, there is sufficient heating from solar radiation to prevent water drops condensation, except on cloudy days. Condensation is a symptom of high relative humidity and may cause significant problems (e.g., germination of fungal pathogen spores, including powdery mildew).

4.2.4 Combined Use of Heating and Ventilation

A common dehumidification practice is simply to open the ventilation openings, allowing moist greenhouse air to be substituted by relatively dry outside air. This method does not consume any excess heat available in the greenhouse, and then ventilation is needed to reduce the greenhouse temperature. However, when the ventilation required reducing the temperature is less than that needed to remove moisture from the air, dehumidification consumes energy. Warm greenhouse air is replaced by cold, dry outside air, lowering the temperature in the greenhouse.

4.2.5 Absorption Using Hygroscopic Material

During the process, moist greenhouse air comes into contact with the hygroscopic material, releasing the latent heat of vaporization as water vapor is absorbed. The hygroscopic material has to be regenerated at a higher temperature level. A maximum of 90% of the energy supplied to the material for regeneration can be returned to the greenhouse air with a sophisticated system involving several heat exchange processes including condensation of the vapor produced in the regeneration process.

4.2.6 Condensation on Cold Surfaces

Wet humid air is forced to a cold surface located inside the greenhouse and different from the covering material. Condensation occurs on the cold surface, the water is collected and can be reused, and the absolute humidity of the wet greenhouse air is reduced. One meter of finned pipe used at a temperature of 5°C can remove 54 g of vapor per hour from the air at a temperature of 20°C and with 80% relative humidity.

4.2.7 Forced Ventilation Usually with Combined Use of a Heat Exchanger

Mechanical ventilation is applied to exchange dry outside air with moist greenhouse air, exchanging heat between the two airflows. Based on the results, a ventilator capacity of 0.01 m^3/s is sufficient for all crops [20]. The energy consumption by the ventilators is estimated to be less than 1% of the energy saved [21].

4.2.8 Anti-drop Covering Materials

The use of anti-water drop covering materials is an alternative technology for greenhouse dehumidification. Anti-water drop films contain special additives which eliminate forming of droplets instead of a continuous thin layer of water running down the sides.

4.2.9 Indoor Air Speed

Indoor air speed influences many factors that affect growth, such as transpiration, evaporation, leaf temperature, and carbon dioxide availability. In general, indoor air speed of 6–15 m/min across leaf surfaces facilitates carbon dioxide uptake. At an air speed of 30 m/min, carbon dioxide uptake is reduced to the minimum level, and of 60 m/min, the growth of the plant inside the greenhouse is inhibited.

4.2.10 Root Environment

Rooting media provide plant support, serve as a source of water and plant nutrients, hold water, and permit diffusion of oxygen to the plant root system. During respiration, oxygen moves into roots system, and carbon dioxide moves out. The media should have sufficient pore size and distribution to provide adequate aeration and moisture retention necessary for acceptable crop production. Media range from mineral soil and amended soil mixes to soilless media such as gravel, sand, peat moss, or liquid films (hydroponics system).

Sandy soil provides excellent support and gas exchange but has insufficient water and nutrient supplying capacity (it lacks on holding water). Therefore, plants grown in sand soil would need to be watered three or more times per day, particularly in the summer season. Clay soil has a high nutrient and water-holding capacity and provides excellent plant growth. However, it is poor in gas exchange due to its small particles when the water films of adjacent particles come into close contact, leaving little open space for gas exchange. Consequently, clay soil is a poor root media for plant growth. Water is sometimes used as a root media; it provides water and nutrients but lacks gas exchange and plant support.

Manure has a high cation exchange capacity which serves as a reservoir for nutrients. In addition, it is a good source of nutrients, and micronutrient deficiencies rarely occur when manure is used. As a matter of fact, micronutrient deficiencies present a serious problem. Manure also contains low levels of nitrogen, phosphorus, and potassium as listed in Table 1. Because large quantities of manure are used in media, a significant part of the total requirement of these three macronutrient is meeting. Manure also has a high water-holding capacity, a basic requirement of greenhouse root media.

Peat moss perhaps is being the closest to manure in the functions that it serves in root media and, indeed, has been the component substituted for manure. Often, as in the case of poultry manure, the high ammonia content causes root and foliage injury to the plant. Rotted cow manure is the best type to be used in the greenhouse. Cow manure is incorporated into media at the volume rate of 10–15%. The media is then pasteurized with steam or chemicals. This is necessary in order to rid the medium of harmful disease organisms, insects, nematodes, and weed seed. Following pasteurization, it is very important that each time water is required, a sufficient quantity is applied to ensure leaching so that a buildup of ammonium nitrogen originating from

Table 1 Primary fertilizer nutrient content of some sources of animal manure

	Nutrient content (% of dry weight)		
Type of manure	Nitrogen (N)	Phosphorus (P_2O_5)	Potassium (K_2O)
Cattle (cow)	0.5	0.3	0.5
Horse	0.6	0.3	0.6
Sheep	0.9	0.5	0.8
Chicken	1.0	0.5	0.8
Swine	0.6	0.5	1.0

the manure does not occur. A buildup of ammonium nitrogen contributes to the total soluble-salt content of the root medium and can be detected readily by a soluble-salt test.

4.3 Solar Energy in Environmental Control

Recent interest in sustainability and green buildings has led to an increased focus on solar energy devices for their nonpolluting and renewable qualities. Replacing fossil fuel with domestic, renewable energy sources can also enhance national security by reducing dependence on imported energy.

Rational energy use is fundamental since energy accounts for a substantial proportion of total production costs. Average energy use accounts for 10–30% of total production costs, depending on the region.

Increase in production per unit of energy (energy efficiency) can be achieved through reduction of energy use and/or improvement of production. The major challenge in greenhouse operation is to find ways to contribute to improved energy efficiency combined with an absolute reduction of the overall energy consumption. The optimizing production efficiency is as follows: autumn/winter – maximize the radiation quantity and minimize the energy loss; spring/summer – reduce high temperatures.

For rational use of energy (or fossil fuels) and reduction of greenhouse energy consumption, greater investment is required in order to achieve efficient use of energy (i.e., the amount of product per input of energy), reduction of energy requirement, and replacement of fossil fuels by more sustainable sources.

Rational use of energy depends on efficient energy greenhouse environmental control, which requires knowledge of the physiological processes (photosynthesis and transpiration, crop growth and development), in relation to the various environmental factors (temperature, light, humidity, and carbon dioxide).

However, to achieve the maximum benefits of energy-efficient environmental control, it is essential for the greenhouse itself and the control equipment (heating and ventilation systems, carbon dioxide supply, and lighting) to be properly designed and frequently checked (at least at the start and once during the growth season). For example, optimized designs of heating systems may prevent uneven temperature distribution and subsequent loss of energy and crop yield.

Solar radiation is the first climate parameter to be evaluated, in particular, year-round availability. Day length and solar radiation intercepted by a horizontal surface during daytime hours are measured to determine total daily solar radiation. Another basic climate parameter is ambient temperature.

The type of greenhouse adopted depends on the prevailing climatic characteristics and suitable climate for grown crops.

There are some differences between air temperature and plant temperature as well as between parts of the plant, especially during daytime, depending on the solar radiation intercepted, the water transpiration from plants, and the air movement. Plant root temperature is assumed to be the same as the soil temperature.

A greenhouse is built and operated to produce crops with a high quantity and quality and return a profit to the grower. Latitude angle is the main factor in influencing greenhouse temperature control; solar radiation available inside the greenhouse (sunlight) is the limiting factor in production, especially during winter season. Therefore, greenhouses should be provided for optimum use of available sunlight. The amount of solar radiation available to plants inside the greenhouse is affected by the following factors: structural frame (Quonset, modified Quonset, or gable-even-span), glazing materials (plastic sheets, fiberglass-reinforced plastic or glass), orientation of the greenhouse (east-west or north-south), and surrounding topography (mounts, buildings, or trees), while the amount of solar radiation available outside the greenhouse is affected by the following factors: latitude angle of the location, time of the year (solar radiation in summer is higher than that in winter), time of the day (solar radiation at and around noon is higher than that after sunrise and prior to sunset), sky covering, and clouds (water vapor and dust affecting the solar radiation).

A greenhouse cover with high transmissivity for solar radiation can produce temperature that is higher than desired in the crop zone. Most surfaces within a greenhouse have a high absorptivity for short-wave solar radiation and, thus, convert incoming short-wave solar radiation into long-wave (thermal radiation) resulting in an increase of the thermal trapping. Heat energy exchange during the daylight time is plotted in Fig. 3.

Transmissivity is the percent of short-wave solar radiation transmitted when the sun's rays strike the glazing surface at a right angle to the surface, while emissivity is the ratio of the total solar radiation emitted by a body to the total radiation emitted by a black body of the same area for the same time period.

Total solar radiation flux incident on a surface roof (glazing) of greenhouses is mainly affected by several factors: the tilt angle of the wall surface (vertical and tilted or curved walls), type and number of greenhouse glazing materials, and orientation of the greenhouse.

4.3.1 Crop-Based Environmental Control

Operational control should not aim at control individual environmental factor (e.g., temperature, humidity, and carbon dioxide) but for energy-efficient crop production

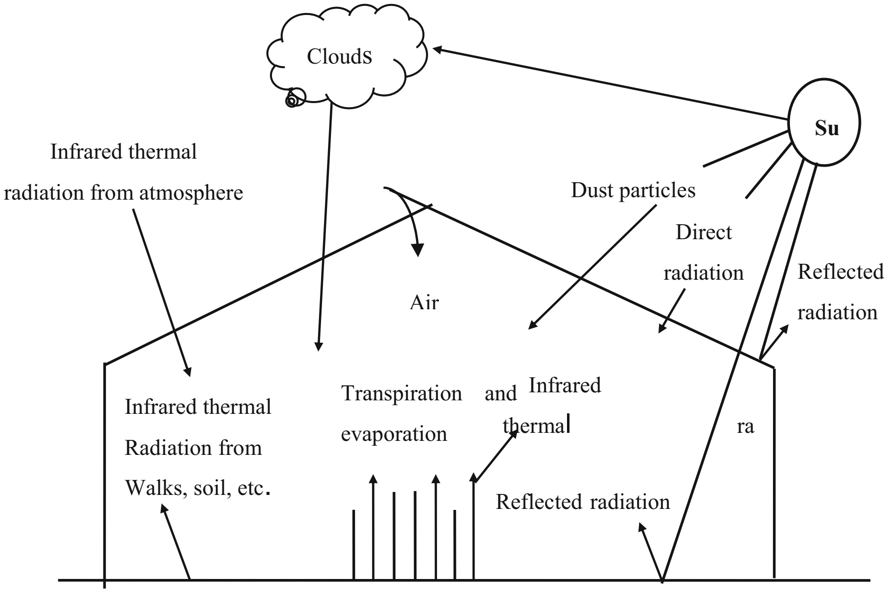

Fig. 3 Energy exchange between a greenhouse and the surroundings

and quality control, taking into account the impact of control actions on both crop yield and energy use.

4.3.2 Evapotranspiration Rate

Evapotranspiration rate of the plants in a greenhouse is mainly affected by the solar radiation received by the leaves of the plant and the stage of plant growth. The ratio of solar radiation to the evapotranspiration for actively growing plants in a greenhouse ranged between 48 and 52% depending upon the total surface area of the plant leaves with an average of 50% (i.e., about one-half of the solar radiation received by the leaves is functioned to evaporate water).

This means that during the first stage of crop growing, the total surface area of leaves is smaller; accordingly, the smaller ratio can be used, whereas the higher ratio can be used during the last stage of growth when the total surface area of leaves is greater. The evapotranspiration rate (q_{ev}) is computed from the following equation [14]:

$$q_{\mathrm{ev}} = RFI_{\mathrm{Tg}}\ \mathrm{W} \tag{6}$$

where R ratio of solar radiation to evapotranspiration, decimal, F ratio of floor surface area cover by plants to the total area, decimal, I_{Tg} total solar radiation flux incident inside the greenhouse

4.3.3 Energy Conservation

Any system functioned in the greenhouse that will reduce heat loss will decrease heating fuel use. A compromise may be necessary to satisfy the light requirement for plant growth while reducing heat loss. For example, the second layer of light-transmitting material will reduce conduction and convection heat loss by about 50%, while the light transmission will decrease by about 10% of a single layer. Movable insulation (thermal screen) can be installed, that is, stores heat energy during daylight time (mainly from the solar radiation) and encloses that heat energy in the crop volume at nighttime. A properly installed double glazing layer or thermal blanket will also reduce air exchange between the crop and outdoor air.

4.3.4 Energy Reduction in Practice

The reduction of the energy need is related to the grower's strategic options in relation to greenhouse construction, covering material, and environmental control equipment in terms of heating system, ventilation, cooling, screens, etc. Increased investment is required and needs to be considered in terms of return rate on investments.

4.3.5 Rational Energy Use in Practice

While the introduction of new modern environmental control technologies will increase energy use efficiency, major advances can be made by enhancing the hardware design of heating and ventilation systems to increase the accuracy and the frequency of controls of the sensor network. Thus, the major applied recommendations for rational energy use mainly depend on the grower's operational control of the available hardware in terms of heating, ventilation and cooling systems, screens, etc.

4.3.6 Replacement of Fossil Fuel by Other Sustainable Sources

As carbon dioxide emission is directly related to the use of fossil fuels for heating and cooling greenhouses, alternatives (e.g., solar and geothermal energy, biomass, and waste heat) can significantly help achieve the reduced carbon dioxide emission targets. Using waste heat and carbon dioxide supply from combined heat and power generators (CHP) and feeding the electricity to the national grid can save a significant fraction of the fuel. While energy is not directly saved at greenhouse level, CHP reduces greenhouse gases emission at the national level by reducing the carbon dioxide emission of the central power plants. However, the economically feasible application of CHP mainly depends on the local situation. Sometimes it is not allowed or is not technically feasible to feed electricity into the national electricity grid, or the price of electricity is too low. Standalone use of CHP (for electricity used at greenhouse farm level) is only an option in large-scale greenhouses and requires smart solutions for the imbalance between the unsynchronized heat and power use at the farm level, for example, using heat storage systems.

Biomass and anaerobic digestion are a good alternative option for fossil fuel, but the availability and massive quantities needed as well as uncertainty about the energy content are major drawbacks for large-scale application. For example, 1 MW of electricity may require up to 2,500 tons of dry mass per year. This not only requires significant investments but also logistic solutions and the availability of biomass in the surrounding area. Furthermore, the continuity of the biomass supply may be a problem as the storage of required amounts of gas is almost impossible. With regard to carbon dioxide from this gas, special attention should be paid to pollution aspects after burning components like SO_2/SO_3 and NO_x may seriously damage the crop. However, for small-scale application and stand-alone greenhouses, they are performing well without connection to energy infrastructure.

5 Greenhouse Heating

Greenhouse heating is essential even in Egypt with a temperate climate, in order to maximize crop production in terms of yield quantity and quality. Heating cost is not only directly connected to profitability, but in the long term, it may determine the sustainability of the greenhouse industry. In addition to the costs of high energy consumption, heating is associated with environmental problems through the emission of greenhouse gases.

Heating of greenhouses accounts for 30–35% of the total cost of production of most protected cropping, and any increase in the price of fuel has a large proportionate effect on production costs.

The requirements for heating a greenhouse reside in the task of adding heat at the rate at which it is lost. Most heat is lost by conduction through the glazing materials (aluminum sash bars, polyethylene, and asbestos-cement curtain walls) of the greenhouse.

The designs and sizes of greenhouse structures used in commercial production influence the indoor air temperature and air circulation patterns, due to the high air temperature that is mainly accumulated in the greenhouse ridge. The heat loss at nighttime in a polyethylene-covered greenhouse represented almost 39% of the total heat loss, providing no condensate was present. The presence of condensate on a polyethylene cover has been reported to decrease heat loss by 10–15%. Infiltration of cold air through improperly fitted ventilation, louvers, and cracks in the cover all contributes to increased heat requirements (heat energy losses up to 16% through the chimneys).

The major heat loss is through the greenhouse structure and covers. Heat energy exchange between indoor and outdoor environments is illustrated in Figs. 4 and 5. Heat energy exchange between the greenhouse indoor and outdoor air is the sum of heat energy available from all sources such as solar radiation heat, furnace heat,

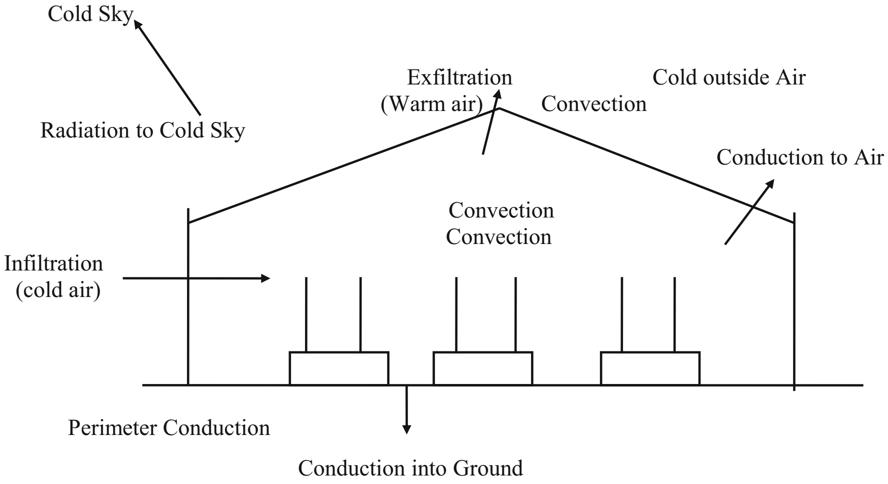

Fig. 4 Heat losses from a greenhouse

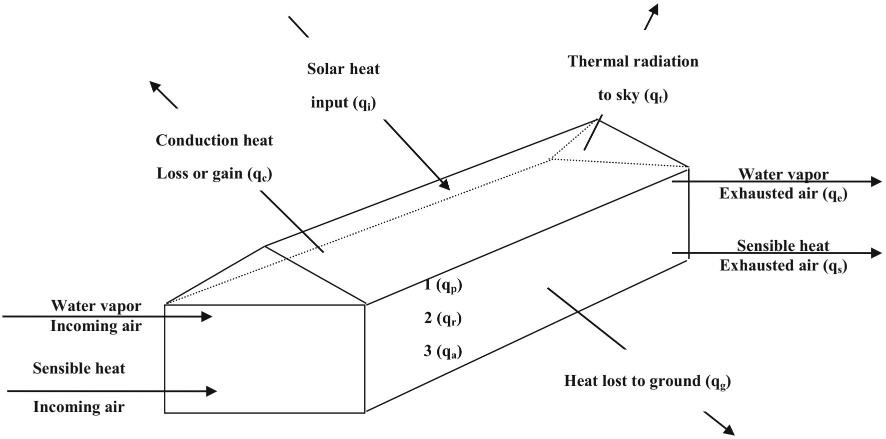

Fig. 5 Heat energy quantities considered in the greenhouse heat energy balance [14]

lighting heat, electric motor heat, etc. and the rate of heat energy loss from the greenhouse. The heat energy balance equation is as follows:

$$q_{\text{input}} = q_{\text{output}} \tag{7}$$

q_{input} = solar radiation + furnace + electric motors + lighting, q_{output} = heat loss by conduction through the greenhouse shell + heat loss by air exchange between indoor and outdoor air + heat loss by thermal radiation to the sky + heat loss by evaporating water

Furnace heat energy is estimated for nighttime heating when there is no solar radiation, and the heat energy from electric motors and lighting and its use in evaporating water may be ignored due to their small values.

During daylight time, the energy balance equation can be written as follows:

$$q_\mathrm{i} = q_\mathrm{c} + q_\mathrm{e} + q_\mathrm{t} + q_\mathrm{s} \tag{8}$$

where q_i solar heat energy input

$$q_\mathrm{i} = R\tau_\mathrm{s}A_\mathrm{f} \tag{9}$$

q_c = conduction heat energy loss or gain, q_e = water vapor loss by exhausted air (evapotranspiration rate)

$$q_\mathrm{e} = FRq_\mathrm{i} \tag{10}$$

q_t = thermal radiation to the sky

$$q_\mathrm{t} = \varepsilon_\mathrm{i}\tau_1 A_\mathrm{f}\sigma\left(T_\mathrm{ai}^4 - T_\mathrm{sky}^4\right) \tag{11}$$

$$T_\mathrm{sky} = 0.0552(T_\mathrm{ai})^{1.5}\ ^\circ\mathrm{K} \tag{12}$$

q_s = sensible heat energy loss by exhausted air.

5.1 Computing Heating Requirements

The heat energy requirements for most greenhouse structures are based on the total heat energy loss from the greenhouse and of heat energy at the rate of which it is lost. Heat energy loss from the greenhouse is much higher than from modern conventional housing. This is due to the high rate of heat transfer through the light-transmitting cover, usually plastic or fiberglass. Many factors contribute to heat energy loss (structure frame, covering materials, orientation, and heating systems).

The total heat losses from inside to outside of the greenhouse can be computed from the following equation [14, 22]:

$$q_\mathrm{Heat} = q_\mathrm{Loss}\ \mathrm{W} \tag{13}$$

$$q_\mathrm{Loss} = q_\mathrm{cl} + q_\mathrm{inf}\ \mathrm{W} \tag{14}$$

where q_cl is the combination of heat losses by conduction, convection, and radiation through the glazing materials and the concrete blocks of the greenhouse. It can be estimated by the following equation:

$$q_{\mathrm{cl}} = U_{\mathrm{o}} A_{\mathrm{c}} (T_{\mathrm{ai}} - T_{\mathrm{ao}})\ \mathrm{W} \tag{15}$$

where U_{o} the overall heat transfer coefficient, W/m^2/C (Table 2), A_{c} the total surface area of covering material, m^2, T_{ai} the indoor air temperature, °C, T_{ao} the outdoor air temperature, °C

The heat loss due to air infiltration through the structure (q_{inf}) of outside cold air can be divided into sensible and latent heat. The heat energy quantity associated with having to raise the temperature of outdoor infiltration cold air up to indoor air temperature is the sensible heat component (q_{S}).

The heat energy quantity associated with net loss of moisture from the space is classified as the latent heat component (q_{L}). The heat energy required to warm outdoor air entering the greenhouse by infiltration to the indoor air temperature is given by [14, 22]:

$$q_{\mathrm{inf}} = q_{\mathrm{S}} + q_{\mathrm{L}}\ \mathrm{W} \tag{16}$$

$$q_{\mathrm{S}} = m_{\mathrm{a}} C_{\mathrm{pa}} (T_{\mathrm{ai}} - T_{\mathrm{ao}})\ \mathrm{W} \tag{17}$$

where m_{a} mass flow rate of cold air, kg/s

$$m_{\mathrm{a}} = \mathrm{MN}$$

$M =$ greenhouse volume (m^3) × density of air (kg/m^3), $N =$ air infiltration rate, s^{-1}, $C_{\mathrm{pa}} =$ specific heat of air.

When the addition of moisture to the indoor air is required to maintain winter comfort conditions, it is necessary to determine the energy needed to evaporate an amount of water equivalent to what is lost by infiltration (latent heat component of infiltration heat loss). This energy may be calculated by

Table 2 Overall heat transfer coefficient for greenhouse cover materials and systems [22]

Greenhouse cover material	Overall heat transfer coefficient (W/m^2 °C)
Single layer glass	5.40
Single layer plastic film	6.80
Single layer fiberglass-reinforced plastic	5.70
Double layer plastic film	3.98
Double layer acrylic	2.84
Double layer plastic film over glass	2.84
Single layer glass plus internal thermal blanket	2.84
Double layer plastic film plus thermal blanket	2.27
Standard concrete blocks, 20 cm thick	2.90
Poured concrete, 15 cm thick	4.26
Perimeter, non-insinuated	4.54
Perimeter, insulated	2.27

$$q_L = m_a h_{fg} (W_i - W_o) \text{ W} \tag{18}$$

where h_{fg} latent heat of vaporization of water, 2,454 × 10^3 J/kg, W_i humidity ratio of the greenhouse indoor air, kg/kg$_{\text{dair}}$, W_o humidity ratio of the greenhouse outdoor air, kg/kg$_{\text{dair}}$

5.2 Heating Equipment

A boiler or heater must be provided to supply heat energy to the greenhouse at the same rate at which it is lost by conduction, infiltration, and radiation. A central or localized heating system may be utilized in larger commercial greenhouse ranges. In the central heating system, one or more boilers are situated in a single position, and the steam or hot water generated is piped to the various greenhouse locations. The localized heating system makes use of several heaters, usually forced hot air, each located in the area it heats.

The recent increases in fossil fuel prices have led to the greenhouse industry to seek for alternative fuel sources to provide heat energy and carbon dioxide for crop production. It is chosen alternative energy source such as the use of solar energy, biogas energy, biomass energy, and hybrid heating systems (solar and biomass or solar and biogas energies), for improving its efficacy in sustainable production and productivity of crops. Field residue biomass is a renewable resource that is considered as greenhouse gas neutral when converted into heat energy properly. Nowadays, there are four different types of heating systems that are commonly used for heating the commercial greenhouses: central heating system, localized heating system, solar heating system, and renewable energy system [23].

5.2.1 Central Heating System

A central boiler system is best justified for the greenhouse range which starts out large (4,000 m^2) and makes its expansions in large increments. It was usually located in a boiler room separate from the greenhouse. When the boiler is separated from the greenhouse, considerable heat energy is lost from the boiler jacket, the pipes carrying steam or hot water to the greenhouse, and the return lines carrying condensate or cool water back to the boiler. When the boiler is in the greenhouse, the escaping heat contributes toward the heat requirement of the crop. However, the high humidity results in corrosion and premature breakdown of switches, pump motors, etc.

Hot water has been customarily supplied to a greenhouse at a temperature range from 82 to 95°C in 50.8 mm pipe diameter. To provide an adequate uniform distribution of heat energy generated by the boiler, a heat-distributing coil (heat exchanger) must be functioned. Circulating pumps are required to move the hot water through the heating system.

Placement of heat-distributing coil is very important; if the entire pipe is stacked on the side walls and end walls of the greenhouse, undesirable patterns of airflow will occur. The heat from the side coils of pipe rises along the side wall and part of the roof until it meets a stream of air which is being cooled by the glazing material and is flowing downward under the roof. The two currents mix and drop at this point, part returning to the pipe coil and part moving toward the center of the greenhouse at the plant level, creating a cold spot in the center. In the center of the greenhouse, currents meet from both sides and rise. The growth of plants is delayed where these cold spots occur as shown in Fig. 6.

A continuous pipe is used in a trombone coil (steam system) (Fig. 7). Resistance to flow is not a problem for steam, but the rapid drop in pressure and temperature along the pipe occurs. Steam enters at the top of the coil and passes to the distance end of the greenhouse. It returns to the entry end of the second pipe down and then back to the distance end in the third pipe down. This arrangement continues until at the end of the coil water condensates and steam enters a trap which permits the return of water, but not steam, to the boiler.

Steam or hot water is produced, plus a radiating mechanism in the greenhouse to dissipate the heat (Fig. 8). The typical cost of a central boiler system depends on the number of heat zones and the exact heat requirement.

Unlike the unit heater systems, a portion of the heat from central boiler systems is delivered to the root and crown zone of the crop, resulting in improved growth and to a higher level of disease control. Placement of heating pipes is very important as it is directly related to heat loss; for example, the placement of pipes in the walls resulted in high losses through the sides.

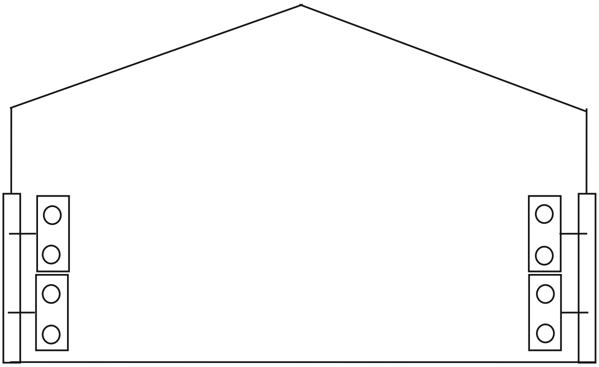

Fig. 6 Heat-distributing system using finned pipe for perimeter of greenhouse

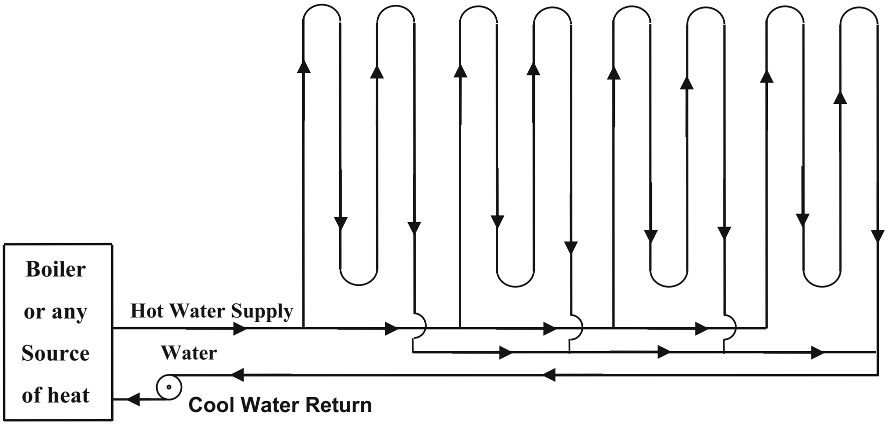

Fig. 7 Heat-distributing coil (heat exchanger) using trombone (series flow) system

Fig. 8 Heating pipes for dissipating the produced heat

5.2.2 Wall Pipe Coils

Perimeter-wall heating can provide part of the additional heat requirement and contribute to a uniform thermal environment in the greenhouse (Fig. 9). Both bare and finned pipe applications are common. Side pipes should have a few centimeters of clearance on all sides to permit the establishment of air currents and should be located low enough to prevent the blockage of light entering through the sidewall.

Fig. 9 Wall pipes

5.2.3 Overhead Pipe Coils

An overhead coil of pipes across the entire greenhouse results in heat loss through the roof and gables. The overhead coil is not the most desirable source of heat, as it is located above the plants; nevertheless, overhead heating systems can provide the additional heat required for winter months. They can also be used to reduce the risk of *Botrytis cinerea* outbreak, a major concern for many greenhouse growers.

5.2.4 In-Bed Pipe Coils

When the greenhouse layout allows it, the in-bed coil is preferable by placing the heating pipes near the base of the plants; the roots and crown of the plants receive more heat than in the overhead system. Air movement caused by the warmer underbench pipe then reduces the relative humidity around the plant. Heat is also kept lower in the greenhouse resulting in better energy efficiency. Such systems are suitable for plants grown on benches, fixed tables, and rolling or transportable tables.

5.2.5 Floor Pipe Coil

Floor heating is more effective than in-bed pipe coil heating. In addition to the advantages of in-bed coils, floor heating has the ability to dry the floor quickly. This is essential when flood floors are used for irrigation/fertilization. In this system, plants are set on the floor, which makes drying the floor difficult. Air movement caused by the warmer floor reduces the relative humidity around the plant.

Such systems are suitable for plants directly grown on the floor, flooded floor areas, or work areas.

5.2.6 Pipe/Rail Heating Systems

These systems maintain uniform temperatures with a positive effect on the microclimate. Air movement caused by the warmer pipe/rail reduces humidity around the plant. Such systems are suitable for vegetable production (see Fig. 10).

5.2.7 Localized Heat System

Numerous heater designs are fit into three basic categories: unit or forced-air, convection, and low-energy radiant heaters.

5.2.8 Unit Heaters

The most common and least expensive is the unit heater system. Unit heaters are often referred to as forced-air heaters. They consist of three functional parts: Fuel is combusted in a firebox to provide heat energy. The heat is initially contained in the exhaust, which rises through a set of thin-walled metal tubes on its way to the exhaust stack. The warm exhaust transfers heat to the cooler metal of the tubes. Much of the heat energy is removed from the exhaust by the time it reaches the stack through which it leaves the greenhouse. A fan in the back of the unit heater draws in greenhouse air, passing it over the exterior side of the tubes and then out the front of the heater to the greenhouse environment again. The cool air passing over the hot metal tubes is warmed. In short, the metal tubes serve as heat exchangers, absorbing heat from the hot exhaust passing through the inside of them and transferring it to the cool greenhouse air passing over the outside of them. Heaters are located throughout the greenhouse, each heating a floor area of 180–500 m^2. Generally the fuel supply

Fig. 10 Pipe/rail heating systems

and fan are connected to a thermostat located in an appropriate area of the greenhouse. Unit heaters come in vertical as well as horizontal designs. This refers to the direction in which the heated air is exhausted from the heater. The vertical heater takes air in from the ridge area of the greenhouse and expels it downward the floor.

These heaters are suspended from the ridge of the greenhouse, well above head height, and are spaced along the length of the greenhouse at intervals equal to its width. Uneven temperatures and drying of the soil sometimes occurred, which resulted in nonuniform growth.

The uneven temperature and drying problems are reduced with horizontal air distribution. It is possible to use fewer but larger heaters, thus reducing the initial cost of the heaters as well as the labor or installation. The horizontal heaters are also adaptable to the newer integrated systems of heating, cooling, and horizontal airflow. Unit heaters (either vertical or horizontal) have an exhaust stack, which is generally run from the heater directly through the roof above the heater (extend 2.4–3.7 m above the firebox).

5.2.9 Convection Heaters

Convection heaters are commonly used in small commercial greenhouses. Fuel of most any type, including wood, coal, oil, or gas, is combusted in a firebox. The resulting hot fumes pass out through an exhaust pipe which is situated along the floor either between floor beds or beneath benches as illustrated in Fig. 11. It is important in all greenhouse heating systems that the exhaust does not contact the crop.

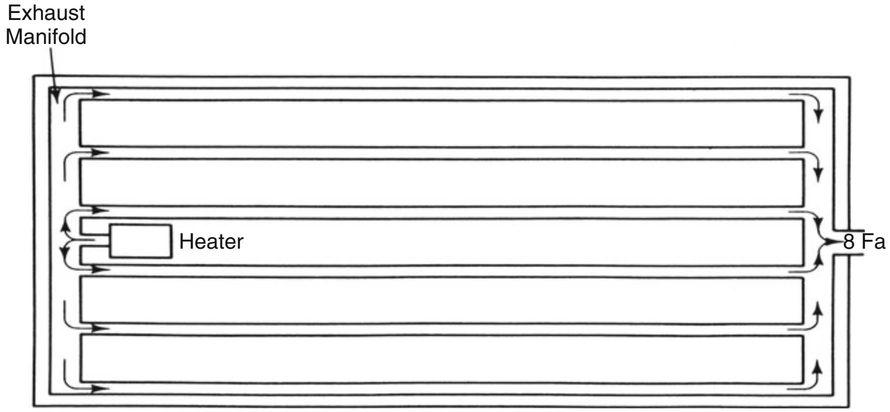

Fig. 11 Exhaust from the convection heater enters a large-diameter stovepipe manifold in which it is distributed to several smaller-diameter stovepipes running along the floor between beds or under benches to the opposite end of the greenhouse

5.2.10 Radiant Heaters

Low-energy, infrared radiant heaters are placed overhead in the greenhouse. They emit infrared radiation, which travels in a straight path at the speed of light (3.8 m/s). Objects (plants, walks, and benches) in the path absorb this electromagnetic energy, which is immediately converted to heat; they in turn will increase temperature of surrounding air. Air temperatures in greenhouses which use infrared radiant heating can be 3–6°C lower than in conventionally heated greenhouses with the same plant growth and production.

Disease is discouraged by the lesser amount of condensation in infrared radiant-heated greenhouses.

The advantage of infrared radiant heat system is the reduction of about 75% in electrical consumption and a 30–50% fuel reduction over a conventional unit heater system. The only motor required in the infrared radiant heat system is in the exhaust fan. Moreover, the selection of heating equipment depends strongly upon the size and type of greenhouse operation, structures and availability, and cost of fuel system components. A system is made up of fuel burner, heat exchanger (heat-distributing coil), and control system.

5.2.11 Solar Heating

Solar heating is an alternative to a fossil fuel heating system. The solar heating system is commonly consists of several components as demonstrated in Fig. 12: solar collector, heat storage facility, heat exchanger to transfer the solar-derived heat to the greenhouse air, backup heater to take over when the solar heating system does not suffice, and set of controls.

5.2.12 Solar Collector

The flat-plate solar collector consists of a flat black plate (aluminum sheet, copper sheet or stainless steel sheet, etc.) for absorbing the maximum possible amount of

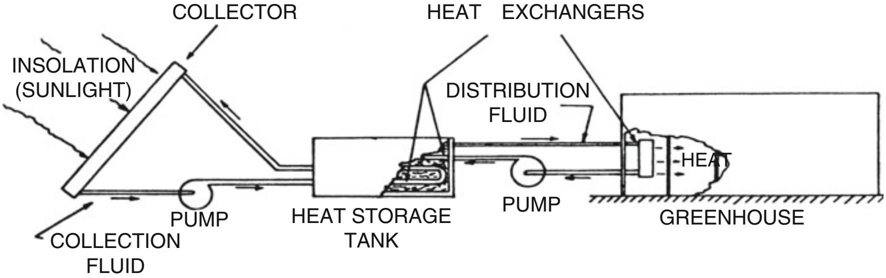

Fig. 12 A typical solar heating system for greenhouses

solar energy. The plate is covered on the sun side by one or more transparent glass or plastic layers and on the back by insulation. The enclosing layers serve to hold the collected heat energy within the solar collector. Water or air is passed through or over the black plate to remove the entrapped heat energy and carry it to the storage facility. Collection of heat energy by flat-plate solar collectors is most efficient when the solar collector is positioned perpendicular to the sun at solar noon. Water collectors require a mass flow rate between 0.4 and 1.2 kg/min per square meter of collector surface area.

A greenhouse itself is considered as a solar collector; some of its collected heat energy is stored in the soil, plants, structural frame, walks, etc. The remaining heat energy can be excessive for plant growth and is therefore vented outdoor. The excess vented heat could just as well be directed to a rock bed for storage and subsequent use during a period of heating (at nighttime).

5.2.13 Storage and Heat Exchanger

Water and rocks are the two most common storage materials for heat in the greenhouse at the present. To store equivalent amounts of heat energy a rock bed would have to be three times as large as a water tank. A water storage system is well adapted to a water collector and a greenhouse heating system making use of a pipe coil or unit heater with water coil contained within. Heated water from the solar collector is pumped to the storage tank during the daylight. As heat is required, warm water is pumped from the storage tank to a hot water or steam boiler or into the hot water coil within a unit heater. Although the solar-heated water will be cooler than thermostat setting on the boiler, heat will be saved, since the temperature of this water will not have to be raised as high to reach the output temperature or steam from the boiler.

5.2.14 Backup Heater

A solar heating system is considerably more expensive than a conventional heating system. A conventional fossil fuel backup system is installed to meet the additional heating needs of the coldest nights. This compromise increases the chances of justifying the cost of a solar heating system. Recently there is a functional possibility of using the stored thermal energy from the hybrid heating system (modern biomass combustion system-assisted flat-plate solar collectors or biogas energy-assisted solar heating system) with a heat exchanger to provide and maintain an optimum level of microclimatic conditions of the greenhouse at nighttime during winter season.

5.2.15 Thermostats and Controls

Various types of thermostat and environmental controllers are available for commercial greenhouse production. Sensing devices should be placed at plant level (at least 1 m above ground) in the greenhouse: thermostats at eye level are easy to read but do not provide the necessary input for optimum environmental control. An appropriate number of environmental sensors are needed throughout the production area. Environmental conditions can vary significantly within a short distance. Thermostats should not be placed in the direct sun rays as this would result in poor readings; they should be mounted facing north or in a protected location. It may be necessary to use a small fan to pull air over the thermostat to get appropriate values. To illustrate typical controls in a solar-heated greenhouse, water system is considered. The first control activates when water in the solar collector becomes 5°C higher than in the storage tank and cuts off when the differential is 2°C. Water is pumped from the solar collector to the top of the storage tank. Cooler water at the bottom of the storage tank returns to the solar collector. A second control might activate the storage tank to the greenhouse heat-exchanger pump when the greenhouse air temperature drops to 16°C and turn it off when 18°C is achieved for most protected cropping. A third control on the backup heater at an air temperature of 16°C in the event that the solar heating system fails to hold the desired temperature.

5.3 Calculation of Greenhouse Heating Needs

1. Measure the first three dimensions of the greenhouse [measure the length, width, and height of the structure (to where the roof begins)].
2. Measure the greenhouse ridge (measure the distance between the ground and the tip of the greenhouse's roof).
3. Measure the greenhouse roof slope (the slope is the distance from the tip of the roof to the bottom of the roof).
4. Determine the surface area of the greenhouse's roof slope and two walls (use the formula: $2(H + S)L$; where $H =$ height, $S =$ roof slope, and $L =$ length).
5. Determine the surface area of the remaining two walls (use the formula: $(R + H)W$; where $R =$ ridge, $H =$ height, and $W =$ width).
6. Determine the total surface area of the greenhouse (add together the results from steps 4 and 5).
7. Calculate the desired temperature difference (determine the best temperature for the interior of the greenhouse, determine the average coldest temperature for the area surrounding the greenhouse, and determine the difference between the two temperatures).
8. Estimate the overall heat loss coefficient (according to the covering material, refer to Table 2) [22].
9. Estimate the heating needs of the greenhouse (multiply steps 6, 7, and 8).

Or, in order to determine the burden of heating requirement, the surface area of an A-frame greenhouse must be divided into four different components, as shown in Fig. 13. These components are: curtain wall, vertical wall, gable end, and gable roof. The areas of each component must be precisely determined in order to calculate the

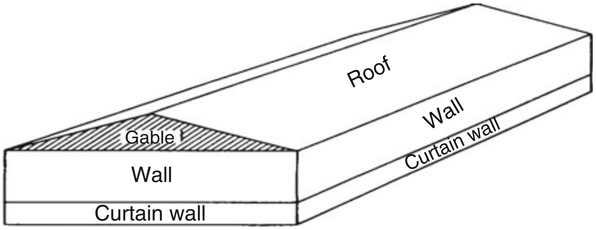

Fig. 13 Schematic diagram of an A-frame greenhouse showing component areas in the determination of heating burden requirement for this greenhouse

heat loss separately from each one. There is also a heat loss from the perimeter of the greenhouse, thus the perimeter must be determined. The heat loss from each area and from the perimeter can be determined by multiplying them by two factors: overall heat transfer coefficient and temperature potential difference between indoor and outdoor air. The burden of heating requirement for greenhouses can be reduced by installing a second covering of polyethylene, by repairing broken glass, by tightening existing glass or sealing the glass laps, by using a windbreak of row of trees to reduce wind velocity, by using high-efficiency heaters and boilers, and possibly by using cool-temperature-tolerant varieties of plants.

6 Greenhouse Cooling

Reducing indoor air temperatures is one of the main problems facing greenhouse management in warm and hot climates. One of the most efficient ways to reduce the difference between indoor and outdoor air temperature is the ventilation system. Natural or passive ventilation system uses very little external energy as opposed to active or forced ventilation, but it increases the complexity of greenhouse structure and makes climate control more difficult. Various technical equipment can efficiently contribute to maintain greenhouse indoor air temperature and relative humidity at acceptable levels during hot periods.

Indoor air temperatures of the greenhouse are frequently 15°C higher than those outdoor in spite of open ventilators. Detrimental effects of high temperatures are typified by loss of stem strength and flower size of carnations and delay of flowering or even bud abortion of chrysanthemums. There are two main cooling systems used for reducing excessive indoor air temperature of greenhouse, natural and mechanical ventilation systems.

6.1 Natural Ventilation Systems

Natural ventilation is the most common method of cooling, and optimizing the geometry of the greenhouse can enhance natural ventilation. Natural ventilation is a direct result of pressure difference created and maintained by wind or air temperature gradients, and it depends heavily on evapotranspiration cooling provided by the crop to maintain acceptable air temperature within the greenhouse. Its suitability as a primary means of cooling must be judged based on local environmental conditions, type of crop grown, and the design of the greenhouse. Natural ventilation may be used to advantage in moderately warm or hot climates, depending on the wind speed. Crops capable of high rates of transpiration should be chosen to maximize evaporation cooling.

Natural ventilated greenhouses are typically provided with vent openings on both sides of the ridge and on both sidewalls. Vent operation should be such that the leeward vents are opened to produce a vacuum at the top of the ridge. Opening of the windward vents produces a positive pressure in the greenhouse which is typically less efficient than vacuum operation. Pressure gradients are typically small so that large vent openings are necessary to provide adequate ventilation. The combined sidewall vent area should equal the combined ridge vent area, and each should be at least 15–30% of the floor surface area; over 30%, the effect of additional ventilation area on the temperature difference was very small [24].

Ridge vents should be hinged and should run continuously to the full length of the greenhouse. The vents should form a 60° angle with the roof when fully open.

Open roof designs may eliminate the need for side or end wall roof vents when more than 50% of the roof area is open. Any natural ventilation system should have the means to open partially or fully in response to indoor air temperature, with automatic control of such systems highly recommended. Incremental opening-closing should also be possible. Automatic vent systems should be equipped with rain and wind sensors to permit closing during periods when crop or ventilator damage might occur.

With roof ventilators, the highest ventilation rates per ventilator area unit are obtained when flap ventilators face the wind (100%), followed by flap ventilators facing away from the wind (67%); the lowest rates are obtained with rolling ventilators (28%).

Shade screens and whitewash are the principal measures taken to reduce incoming solar radiation; greenhouse ventilation is an effective way to remove extra heat through air exchange between the inside and outside (when the outside air temperature is lower). If the outside wind speed is not too low, natural ventilation can be more appropriate, creating a more humid and cooler (albeit less homogeneous) environment around the canopy.

Sufficient ventilation is very important for optimal plant growth, especially in the case of high outside temperatures and solar radiation during the summer in Egypt.

6.2 Insect-Proof Screens for Good Agricultural Practices

Most greenhouses are equipped with ventilation openings to provide suitable microclimate conditions for plant growth. Unfortunately, these vents serve also as a major port of entry for pests, then growers are forced to cover these vents completely and permanently with fine mesh screens net to prevent pest invasion. Since the pests can be very small (e.g., whiteflies and thrips), very fine mesh screens net are required to prevent their entry; these screens impede ventilation and, in some cases, reduce light transmission [10]. Moreover, the targeted insects are most abundant during the warm and hot seasons when effective ventilation is essential for avoiding stressful conditions for both crop plants and workers [25].

Screens are characterized by their porosity (number between openings per inch), mesh size, thread dimension (diameter or thickness), texture (woven, knitted, woven/knitted), color, light transmission/reflection, and resistance to airflow. Most insect-proof screens have square or rectangular openings and are made of monofilament threads.

6.2.1 Effect of Insect-Proof Screens on Ventilation

An important consideration when designing a screen-proof net installation is the effect that screen materials have on airflow through the openings. It has been well documented that screens increase the air pressure drop on the openings, which results in reduced greenhouse ventilation. It is also well known that the air pressure drop on screens is mainly a function of screen porosity (mesh number). For a woven screen made of a monofilament thread and with a simple texture, it is possible to calculate the screen porosity (ε) from the geometric dimensions of the screen:

$$\varepsilon = \frac{(l - d)(m - d)}{ml} \tag{19}$$

where l and m are the distance between the centers of two adjacent weft and warp threads, respectively, d is the diameter of the threads.

Teitel [26] suggested the following correlation to estimate the effect screens on the vents have on temperature difference between greenhouse and ambient air with screens(ΔT_{SW}) and without screens(ΔT_{W}):

$$\Delta T_{\mathrm{SW}} = \Delta T_{\mathrm{W}}(5 - 4\varepsilon) \tag{20}$$

The relationship between the temperature difference with and without a screen is dependent on greenhouse type, crop, weather, and the exact location where the inside air temperature was measured. The value of porosity increases, the ventilation rate increases, and the inside/outside temperature difference decreases.

6.2.2 Removing Insect Screen from Vents When the Risk of Pest Invasion Is Low

Optimal climatic conditions especially air temperature and relative humidity in the greenhouse are often maintained by closing and opening windows and vents. However, insect screens covering windows and vents are not regulated in response to changes in the pest invasion hazards. Greenhouse ventilation is likely to be improved if ventilation openings are uncovered when there is no pest invasion hazards [13]. In the fall, when the whitefly population peaks, over 97% of whiteflies entered the greenhouse between 7.00 and 13.00 h [27]. Thus, the risk of whitefly entering greenhouses in the afternoon and at night is negligible.

The flight of thrips was studied using sticky pole traps and similar traps mounted on wind vanes. For most of the year, about 85% of the thrips were caught in the morning and 10% at dusk [28]. Flight time was correlated with periods of low wind speed, and thrips were seldom caught with wind >10 km/h [29]. Both whiteflies and thrips are not likely to enter protected crops during the hot and windy afternoon hours or at night. Therefore, insect screens may be removed from vents during those times.

6.2.3 Maximizing the Screened Area

Increasing ventilation in multi-span greenhouses with roof openings can be considered a good choice on which screens are mounted to increase the maximum angle at which the flap can be opened. Another openings with preformed concertina-shaped screens can be used that unfold as the ventilators open and then fold up again when they close. Teitel et al. [30] showed that a concertina-shaped screen allows higher airflow (an increase of about 25%) when compared with a flat screen under similar pressure drops across the screen.

6.3 Trends in Natural Ventilation

Efficient ventilation performance is crucial for greenhouse production in both humid winter and hot summer conditions. The ventilation process contributes to optimal control of air temperature, relative humidity, and concentration of gases within the greenhouse. Thus, photosynthetic and transpiration activities of plants are regulated properly and then enhance greenhouse productivity. Given the advantages, low maintenance, low operational costs, and reduced noise, it is the most inexpensive way to keep suitable greenhouse internal microclimate. However, control of airflow with natural ventilation is limited. Therefore, it is necessary to increase ventilation efficiency.

The driving force for natural ventilation is the pressure difference across the ventilation openings caused by wind and/or thermal effects.

Natural ventilation can be achieved by opening windows at the top of the greenhouse and/or at the sidewalls. The number and size of the windows and the mechanisms for window opening vary, with many different arrangements used in glasshouses and plastic-covered houses. Ridge openings can be classified as continuous or noncontinuous, and they are usually on both sides of the ridge, although hoses with openings on one side only are also constructed. Roof vents are either fixed or fully automatic (movable roof vents).

A fixed overlapping vent on a gable ridge provides ventilation while preventing penetration of rain. Movable roof vents may be formed by film rollup from gutter to ridge; ridge hinged arched vents; vertical openings at the center of the arch running the entire length of the roof; vertical roof openings starting at the gutters and extending to a height of about 1 m; or vertical openings at the center of the arched roof running the entire length of the roof. The position and hinging of the vent at the ridge are the basis of a better evacuation of the hot and humid air which builds up at the top of the greenhouse.

Side ventilation is usually achieved by rolling up curtains with a central mechanism operated manually or by an electric motor, mechanisms that open the side vents from bottom to top. Side openings with flaps hinged from the top are also used; however, they are more common in glasshouses than in plastic-covered houses. Flap ventilators are more efficient than rolling ventilators, particularly under moderate wind conditions.

6.3.1 Wind-Driven Ventilation

When the wind blows around a greenhouse, the wind field generates pressure distribution through the greenhouse. Moreover, wind has a fluctuating character that creates a fluctuating pressure difference over the openings; the mean difference in pressure and the fluctuating pressure difference are responsible for the airflow through the greenhouse ventilators [31]. There are claims that air exchange is proportional to outside wind velocity.

6.3.2 Thermally Driven Ventilation

Under calm conditions, buoyancy forces (differences between inside and outside air densities) are the driving mechanism for ventilation, but the effect of thermal buoyancy on ventilation is of fundamental interest when there is almost no wind. Buoyancy-driven ventilation is more important when wind speeds are below 0.5 m/s [32].

6.3.3 Airflow Characteristics Under Wind-Driven Ventilation

Windward ventilation is preferred to leeward ventilation for greenhouses located in warm areas, since windward ventilation clearly increases the ventilation rate [33]. Nevertheless, the internal climate is generally less uniform with windward ventilation, so new greenhouse constructions have larger openings facing the prevailing winds.

6.3.4 Windward Ventilation

The external air is captured by the vent opening of the first span. This results in an internal flow with the same external air direction. The first windward roof ventilator has the most significant effect on the air exchange intensity and internal airflow [34].

6.3.5 Leeward Ventilation

The external wind follows the windward roof of the first span and accelerates along the roof. The external flow separates from the greenhouse structure at the ridge of the first windward span and creates an area of low speed above subsequent spans. Greenhouse air exits the greenhouse through the first roof ventilator, creating an internal flow which is opposite to the external flow. As for windward ventilation, the first ventilator plays the leading role in the air exchange process [35]. Whenever possible, limit greenhouse width to approximately 50 m [34] and leave a separation between adjacent greenhouses to allow hot air to escape.

6.3.6 Sidewall Ventilation

Sidewall ventilation is similar to windward greenhouse roof ventilation with respect to the airflow pattern, since for greenhouse sidewall ventilation the external air also enters the greenhouse through the windward side and passes along the greenhouse width. Kacira et al. [36] showed that the highest greenhouse ventilation rate was achieved when both side and roof vents were used. Without buoyancy effect in the computations, the greenhouse ventilation rate increased linearly with increasing external wind speed. The ratio of the opening of the ventilator area to the greenhouse floor area (9.6%) was found to be small compared with the recommended ratios of 15–25%. Sidewall ventilation may help to reduce the area of the dead zone with high temperatures typical of wide greenhouses.

6.4 Suggestions to Improve Natural Ventilation

6.4.1 Use of Deflectors

Sase [37] suggested a solution to avoid problems in many types of ventilator, that is, the incoming air mainly follows the inner surface of the roof and creates a crossflow above the crop without mixing with the air in the crop area by the use of screens or deflectors to redirect the air stream, while Nielsen [38] offered a method to direct the passing airflow at the hinged ridge vents into the crop space (Fig. 14). Using 1-m-high vertical screen mounted to the ridge, improvements were achieved in the air exchange in the plant zone of about 50% on average. Kacira et al. [39] evaluated the optimization of the traditional vent

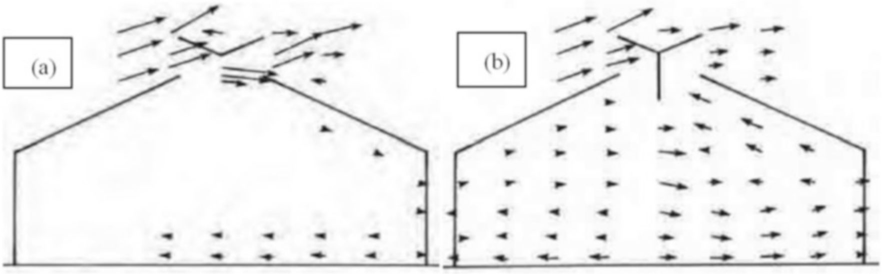

Fig. 14 Effect of a deflector at the roof ventilator on internal air circulation, (**a**) deflector type 1 and (**b**) deflector type 2 [38]

configuration for a two-span glasshouse for better air renewal especially in the plant canopy zone. They evaluated both rollup and butterfly-type side vent openings and various roof vent opening configurations (Fig. 15). The maximum greenhouse ventilation rates were achieved when rollup side vents were used in the sidewalls and both side and roof vents were fully open. The use of the rollup side vent considerably improved the ventilation rate in the plant canopy zone. Thus, the ventilation in the plant canopy zone was considerably affected by the internal airflow patterns caused by different vent configurations.

6.4.2 Changes in the Greenhouse Slope

Increasing the greenhouse roof slope has a positive effect on the ventilation rate. Baeza [34] compared the air exchange rate and internal airflow of greenhouses with roof slopes ranging from 12 to 32°C. According to this study, ventilation sharply increased with increasing roof slopes up to 25°C, after which the increase in ventilation was rather small. The low roof slope does not only affect the ventilation rate but also the air movement inside the greenhouse. Most of the airflow entering through the windward vent on a gentle slope attaches to the greenhouse cover, while with steeper slopes, part of the airflow contributes to the greenhouse ventilation of the first span, and part of it moves on to the following span decreasing the attachment effect observed for lower slopes. Increased roof slope up to 30°C led to increased ventilation rate significantly, and traditional horizontal roof greenhouses are replaced with symmetrical or asymmetrical greenhouses.

6.4.3 Size and Type of Ventilators

Baeza [34] analyzed the effect of ventilator size on greenhouse climate. He increased the flap ventilator size from 0.8 to 1.6 m in the first two and last two spans while maintaining the regular size of 0.8 m in the central spans. For a ten-span greenhouse, the increase in ventilator size had a significant effect on the ventilation rate. Besides, air movement in the crop area was enhanced. As a consequence, the temperature

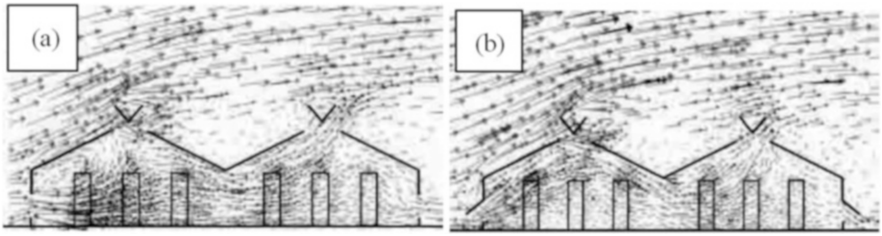

Fig. 15 The effect of side vent configuration on the canopy zone ventilation and air exchange process. (**a**) Rollup side vents and (**b**) butterfly-type side vents [39]

field was more uniform, the temperature difference in relation to the exterior was reduced, and the stagnant air areas were significantly fewer in number and smaller in size. Pérez-Parra [3] compared flap ventilators and rollup ventilators on the greenhouse roof under leeward and windward conditions. Flap ventilators were in all cases more effective at increasing ventilation rate than rollup ventilators. Interestingly, the rollup ventilator's performance was not affected by wind direction, while flap ventilators oriented windward side nearly doubled the air exchange of leeward flap ventilators.

6.4.4 Crop Row Orientation

Sase [40] conducted a ventilation study to compare the effect of the crop rows perpendicular and parallel to the sidewalls. The inside air velocity in the greenhouse with perpendicular rows was nearly twice that of the greenhouse with parallel rows; the crop canopy is a porous medium that offers resistance to the airflow, so it is recommended that the aisle between rows be oriented in the direction of the internal airflow. For roof-ventilated greenhouses, there is strong air movement over the crop area at a higher speed than the air in the canopy zone [35].

6.4.5 New Greenhouse Designs with Improved Ventilation

Upcoming greenhouse models relying on natural ventilation should be narrowed enough (maximum width 50 m) to avoid excessive temperature gradients; furthermore, they should have larger ventilators, especially in the first span facing prevailing winds. They will incorporate screens or deflectors to redirect the airflow toward the crop area producing a homogeneous mixture of the incoming and internal air, to have uniform growing conditions. Effective windward ventilation requires keeping an area between greenhouses free from obstacles. For proper ventilation, future greenhouse designs will not consider a single greenhouse but a group or a greenhouse cluster, since the airflow in a greenhouse is affected by its surroundings.

Natural ventilation is the main method for greenhouse gas exchange, mainly because of the low-energy consumption and low maintenance costs. However, natural ventilation relies on external conditions such as wind speed and wind direction and outside air temperature and relative humidity. Natural ventilation itself may not be sufficient to provide the desired environment. Thus, some other cooling techniques such as shading, mechanical ventilation, or evaporative cooling are used combined with natural ventilation [41–44].

6.5 Mechanical (Fan) Ventilating and Cooling Systems

Mechanical cooling (fans, heat pumps, and heat exchangers) can maintain the same greenhouse temperature as does natural ventilation; it can further reduce the temperature, especially under high ambient temperatures or high radiation levels. With high cooling capacity, it is possible to keep the greenhouse completely closed, even at maximum radiation levels.

Traditional cooling alternatives for greenhouse depend upon exhaust fans to remove excess heat energy. As outdoor air is brought into and then through the house, its energy level rises due to sensible heat gain from the canopy, ground, and surrounding structure. The volume of air required to maintain a given air temperature rise, ($T_{\mathrm{ex}} - T_{\mathrm{inlet}}$), may be estimated using the following approximate energy balance [14]:

$$(1 - E)R_{\mathrm{i}}A_{\mathrm{f}} = U_{\mathrm{o}}A_{\mathrm{c}}(T_{\mathrm{ai}} - T_{\mathrm{ao}}) + \left[\frac{q_{\mathrm{v}}A_{\mathrm{f}}C_{\mathrm{pa}}}{V_{\mathrm{ex}}}\right](T_{\mathrm{ex}} - T_{\mathrm{inlet}}) \tag{21}$$

where E evapotranspiration coefficient, dimensionless, R_{i} solar radiation flux incident inside the greenhouse, W/m^2, A_{f} floor surface area, m^2, U_{o} overall heat transfer coefficient, W/m^2 °C, A_{c} surface area of covering material, m^2, T_{ai} indoor air temperature of the greenhouse (the average of the inlet and outlet air temperatures), °C, T_{ao} outdoor air temperature of the greenhouse, °C, q_{v} ventilation rate, m^3/s m^2 of floor surface area, C_{pa} specific heat of air exhausting greenhouse, J/kg °C, V_{ex} specific volume of air exhausting greenhouse, m^3/kg, T_{ex} temperature of exhaust air leaving the greenhouse, °C, T_{inlet} temperature of air entering the greenhouse, °C

The principle of using forced ventilation is to create airflow through the greenhouse. Fans force air out on one side, and openings on the other side permit air in. Forced ventilation by fans is the most effective way to ventilate the greenhouses, but it consumes electricity energy.

Fine mesh screens obstruct the airflow, resulting in reduced air velocity and higher temperature and humidity, as well as an increase in the thermal gradients within the greenhouse [45].

6.6 Ventilation Cooling and Shading

Removal of heat load can be achieved by reducing incoming solar radiation; removing extra heat through air exchange; and increasing the fraction of energy partitioned into latent heat.

Natural or forced ventilation is generally not sufficient for extracting the excess energy during sunny summer days [46]; even other cooling methods must be used in combination with proper ventilation. The penetration of direct solar radiation through the greenhouse covers into the greenhouse enclosure is the primary source of heat gain. The entry of extra radiation can be controlled by shading or reflection.

6.6.1 Shading

Shading to reduce the solar energy flux into the greenhouse during periods with an excessive radiation level is a common way of achieving passive cooling. Mobile shading systems which installed inside or outside have a number of advantages, such as the improvement of air temperature and relative humidity, quality, and a clear increase in water-use efficiency.

Shading can be achieved in several ways: paints, external shade cloths, nets (of various colors), partially reflective shade screens, and applying water film over the roof and liquid foams between the greenhouse walls. Shading is the last resort to reduce greenhouse air temperature during summer season, because it affects productivity; however, shading can in some cases result in improved fruit quality. A method widely adopted by growers because of its low cost is white painting, or whitening, of the cover material. The use of screens has been progressively accepted by growers and an increase in the area of field crops cultivated under screenhouses [47].

Roof whitening, given its low cost. Baille et al. [48] reported that whitening on glass material enhanced slightly photosynthetically active radiation proportion of the incoming solar irradiance. Therefore, reducing the solar infrared fraction entering the greenhouse is a potential advantage compared with other shading devices with high solar radiation during summer. Another advantage of whitening is that it does not affect ventilation, while internal shading nets adversely affect the performance of greenhouse roof ventilation. Whitening also significantly increases the fraction of scatter irradiance, which is known to enhance radiation use efficiency.

Screens mounted inside the greenhouse also contribute to decreasing the inside air speed, thus lessening the leaf boundary layer and restraining the availability of CO_2 near the leaf surface. It is not clear whether shading nets are best used throughout the growth cycle or only during the most sensitive stages when the crops have a low leaf area and the canopy transpiration rate cannot significantly contribute to the greenhouse cooling [49].

Specific materials which absorb or reflect some wavelengths or contain interference or photo or thermochromic pigments may be used to bring down the heat load, but mostly these materials also reduce the photosynthetically active radiation (PAR) level. Materials reflecting part of the sun's energy not necessary for plant growth [near-infrared (NIR)] show promising results (e.g., [50]) and may be applied either as greenhouse cover or as screen material.

6.6.2 Evaporative Cooling Systems

Evaporative cooling systems is the common technique for reducing sensible heat load by increasing the latent heat fraction of dissipated energy and used to aid greenhouse cooling in warm climates by lowering the dry-bulb temperature of the inlet air. One of the most efficient solutions for alleviating high-temperature conditions is to use evaporative cooling systems, based on the conversion of sensible heat into latent heat through evaporation of water supplied directly into the greenhouse atmosphere (mist or fog system, sprinklers) or via using evaporative pads. Evaporative cooling allows simultaneous lowering of temperature and vapor pressure deficit, and its efficiency is better in dry environments. The advantage of using mist or fog systems over wet pad systems is the uniformity of conditions throughout the greenhouse, eliminating the need for forced ventilation and airtight enclosure.

Direct evaporative cooling by fogging/misting and indirect evaporative cooling (pad and fan) are most likely the result of the positive effects of lower temperature and higher relative humidity resulting in better growth and production, at least with major fruit and vegetables. Therefore, direct evaporative cooling by misting, wet pad, and fan cooling still gives the best economic results and increases energy efficiency primarily through the positive impact on production.

6.6.3 Fog System

Water is sprayed as small droplets (in the fog range, 2–60 nm in diameter) with high pressure into the air above the plants in order to increase the water surface in contact with the air. Free fall velocity of these droplets is slow, and the air streams inside the greenhouse easily carry the drops. This can result in high efficiency of water evaporation combined with keeping the foliage dry.

Fogging is also used to create high relative humidity, along with cooling inside the greenhouse. According to Arbel et al. [51], increased efficiency in the cooling process in relation to water consumption can be expected if fogging is combined with a reduced ventilation rate. Furthermore, the efficiency of fog systems is often limited by insufficient natural air convection, in the absence of wind, and by the risk of wetting the plants when water droplet evaporation is not complete. Fog cooling efficiency increases with spray rate and decreases with ventilation rate [42, 43].

6.6.4 Fan and Pad Cooling

The evaporative cooling system is based on the process of heat absorption during the evaporation of water. The fan-and-pad cooling system is most commonly used in horticulture (Fig. 16). Along one wall of the greenhouse, water is passed through a pad. The pad may be placed vertically in the wall, or it may extend horizontally out from the wall. It is a cross fluted cellulose material somewhat similar in appearance to corrugated cardboard. Exhaust fans are placed on the opposite wall. Cooling pads and air inlets are sized to maintain the face velocities in which inlet air temperature can be expected to reduce to within 2.0°C of the outside wet-bulb temperature at pressure drops through the pads not exceeding 0.015 kPa. Higher face velocities typically result in reduced cooling efficiency.

Water in the cooling pads, through the process of evaporation, absorbs heat from the surrounding pad and frame as well as from the air passing through the cooling pad.

The air entering the greenhouse can be as much as 15–20°C cooler than the outdoor air temperature if the outdoor air relative humidity is lower than 35%.

Outside air is blown through pads with as large a surface as possible and which are kept permanently wet by sprinkling water. The water from the pads evaporates and cools the greenhouse air; relative humidity of outside air must therefore be low. There are basically two systems of fan-and-pad cooling: the negative-pressure system and the positive-pressure system.

- The negative-pressure system consists of a pad on one side of the greenhouse and a fan on the other. The fans suck the air through the pad and through the greenhouse. The pressure inside the greenhouse is lower than the pressure outside; hot air and dust can therefore get into the greenhouse. There is a temperature gradient from pad to fan.
- The positive-pressure system consists of fans and pads on one side of the greenhouse and vents on the another side. The fans blow the outside air through the pads into the greenhouse. The air pressure inside the greenhouse is higher than outside; dust cannot get into the greenhouse.

Fig. 16 Fan and pad cooling system. (*Left*) Exhaust fan located on the leeward side of the greenhouse, (*right*) cross fluted cellulose pads placed vertically in the opposite wall of exhaust fans

In order to achieve optimal temperature during summer, the greenhouse should be shaded. The water flow rate, water distribution system, pump capacity, recirculation rate, and output rate of the fan-and-pad cooling system must be calculated carefully and designed to provide a sufficient pad wetting and to avoid deposition of material.

There are numerous considerations when designing a fan-and-pad cooling system. First, cooling efficiency should provide inside air relative humidity of about 85% at the outlet; higher air relative humidity slows down the transpiration rate of the plants. Plant temperature can then increase above air temperature. It is important that the pad material have a high surface, good wetting properties, and high cooling efficiency. It should cause little pressure loss and should be durable. The average thickness of the pad is 100–200 mm. It is essential that the pad be free of leaks through which air could pass without making contact with the pad.

The pad area depends on the airflow rate necessary for the cooling system and the permissible surface velocity over the pad. Average face velocities are 0.75–1.5 m/s. Excessive velocities may cause problems with drops entering the greenhouse. The pad area should be about 1 m^2 per 20–30 m^2 greenhouse area. The maximum fan-to-pad distance should be 30–40 m.

Pads may be positioned horizontally or vertically. Vertical pads are supplied with water from a perforated pipe along the top edge. In the case of horizontal pads, the water is sprayed over the upper surface. The water distribution must ensure even wetting of the pad. Pads have to be protected from direct solar radiation to prevent localized drying out: salt and sand might clog them if they become dry. The pads have to be located and mounted in a way which allow easy maintenance and cleaning. They should be located on the side facing the prevailing wind direction.

Fans should be placed on the lee side of the greenhouse. If they are on the windward side, an increase of 10% in the ventilation rate will be needed. The distance between fans should not exceed 7.5–10 m, and fans should not discharge toward the pads of an adjacent greenhouse less than 15 m away. All exhaust fans should be equipped with automatic shutters to prevent air exchange when fans are not used and also to prevent back-draught when some are not being used.

When starting the cooling system, the water flow through the pad should be turned on first to prevent the pads from clogging. Fans should not be started before the whole pad has been completely wetted. When stopping the cooling system in the evening, the fan should be turned off before the water flow through the pad. It is recommended to operate the cooling system by a simple control system depending on the inside air temperature. The airflow rate depends on the solar radiation inside the greenhouse – that is, on the cladding material and shading – and on the evapotranspiration rate from the plants and soil. The airflow rate can be calculated by an energy balance. Generally, a basic airflow rate ranged from 120 to 150 m^3/m^2 greenhouse area per hour will allow satisfactory operation of an evaporative cooling system.

There are two main considerations in the evaporative cooling system: the rate at which warm air is to be removed and the area of the cooling pads.

6.7 Rate of Air Exchange

The rate of air removal from the greenhouse must increase as the elevation of the greenhouse site increases. Air decreases in density, becoming lighter with increasing elevation. The ability of air to remove solar heat from the greenhouse depends upon its weight (not its volume) and the light intensity inside the greenhouse (as the light intensity increases, the heat input from the sun increases, requiring a greater rate of air removal from the greenhouse). Solar radiation that penetrated the greenhouse covering material warms the air as it passes from the cooling pads to the exhaust fans. Usually a 4°C rise in indoor air temperature is tolerated across the greenhouse; to reduce the rise in air temperature, it will be necessary to raise the velocity of air movement through the longitudinal direction of greenhouse.

The cooling pads and fans should be located on opposite walls. These walls may be the ends or the sides of the greenhouse. The distance between cooling pads and fans is 30–40 m. The distance <40 m requires expensive equipment, while in the distance >30 m, the cross-sectional velocity of air movement becomes lower, and the air often develops a clammy feeling (it compensated by increasing the velocity of air movement, and this increases the cost of the system).

The exhaust fans should be evenly spaced along the end of the greenhouse, at plant height if possible, to guarantee a uniform flow of air through the plants.

The cooling pads should extend the entire length of the wall in which it is mounted, and this wall should be opposite the wall where the extracting fans are located. The necessary height of the cooling pads is determined by dividing the total area of the pads by the length of the pads.

The cross fluted cellulose cooling pads have the appearance of corrugated cardboard. The cellulose pads are impregnated with insoluble anti-rot salts, rigidifying saturates, and wetting agents to give it its lasting quality, strength, and wettability.

The main disadvantage of cooling pad systems is the creation of large air temperature gradients inside the greenhouse, from pads on one side to extracting fans on the opposite side. The factors mainly affected the air temperature distribution along the greenhouse as follows: ventilation rate, crop transpiration and soil evaporation, percentage of shading, water evaporation from the cooling pads, and the overall heat transfer coefficient of the covering material. The efficiency of evaporative cooling system (η) can be computed by the following formula:

$$\eta = \frac{T_{\mathrm{ao}} - T_{\mathrm{pad}}}{T_{\mathrm{ao}} - T_{\mathrm{oaw}}} \tag{22}$$

where T_{ao} dry-bulb temperature of the outdoor air, °C, T_{pad} air temperature just leaving the cooling pads, °C, T_{oaw} wet-bulb temperature of the outdoor air, °C

6.8 Temperature Gradients in Greenhouse

The main drawback of evaporative cooling systems for greenhouses based on cooling pads and extracting fans is the thermal gradient developed along the airflow direction. High air temperature gradients of this type can markedly affect plant growth, and growers should combine cooling pads with shading. To predict the air temperature gradients along a greenhouse, a simple climate model is proposed which incorporates the effects of ventilation rate, roof shading, and crop transpiration. In order to calibrate the proposed model, measurements should be performed in a larger greenhouse (commercial) equipped with a complete evaporative cooling system using pads and fans and shaded by black plastic screen. The energy balance equation combines five factors which mainly affect the temperature distribution along the larger greenhouse length. The model can be expressed as

$$T_{\mathrm{ai}}(X) = T_{\mathrm{ao}} + A_1 + \left[\left(T_{\mathrm{pad}} - T_{\mathrm{ao}} - A_1\right)\exp(-A_2 X)\right] \tag{23}$$

where X distance, at which the air temperature was measured, m, and the two coefficients A_1 and A_2 are given by

$$A_1 = \frac{R_{\mathrm{i}} A_{\mathrm{f}}(1 - E)}{q_{\mathrm{v}} \rho C_{\mathrm{p}}}\ {}^{\circ}\mathrm{C} \tag{24}$$

$$A_2 = \frac{U_{\mathrm{o}} P}{q_{\mathrm{v}} \rho C_{\mathrm{p}}}(1/m) \tag{25}$$

where ρ air density, kg/m^3, P perimeter of greenhouse, m

7 Water Requirements and Irrigation Management

Plants require adequate moisture for optimum growth and maximum crop production. Water is the medium by which different nutrients are absorbed by the plants. Water absorbed by root system moves through the roots and xylem into branches and leaves. Water vapor is then transpired through stomates in the leaves into the atmosphere surrounding the plant. For each 28 g of dry matter produced by the plant, as much as 7.5 l of water moves through the plant. An adequate and properly regulated supply of moisture will help control plant growth, flowering, and productivity.

Water use by greenhouse plants is directly related to available sunlight. However, less than 2% of the water that enters the roots remains in the plant. Most water passes through the water-conducting tissue and evaporates into the air. Most of the variables in growing plants have been measured and controlled to varying degrees, and optimum levels of air temperature, relative humidity, nutrients, and light are known for most commercial crops. These can be measured and then adjusted with acceptable accuracy. Rooting medium moisture measurement and control information can be installed. Various methods of indicating soil moisture are used, but, to date, no one method is in general use throughout the country. The following are methods used to indicate the moisture content of the soil:

1. Appearance or feel: growers usually water when the soil mix will crumble easily when compressed in the hand. Examination should be made at several soil depths.
2. Tensiometers: this device consists of a porous cup attached to a vacuum gauge. The cup is inserted in the soil and the apparatus filled with water. As soil dries, water leaves the cup, and the resulting tension (vacuum) is recorded on the gauge. Limitations are lack of soil uniformity and variation in the porous cup. Tensiometers must be calibrated for different soil types.
3. Weight of soil moisture: one pot plant on a bench is used as a control. It rests on a scale that is adjusted to trip a switch when the moisture level drops below a certain level. The setting has to be adjusted as the plant grows to compensate for the added plant weight.
4. Light accumulators: this device utilizes a photoelectric cell and counter to activate a solenoid valve when a predetermined quantity of light has been received. It is based on the idea that increased light causes increased evaporation. It does not take into account air movement or variations in soil mix.
5. Evaporation simulators: a stainless steel screen is used to simulate a leaf. It is placed among the plants and receives the same amount of water as the plants. The screen is attached to a switch which activates a solenoid valve when the water that has collected on the screen evaporates. This device is limited to use with misting or overhead irrigation systems.
6. Soil moisture conductivity: several devices relate soil moisture to electrical conductivity. When the soil dries to a preset level, the electronic circuit activates the solenoid valve. Most of the above devices use a timer to shut off the water supply after a predetermined length of time.

7.1 Water Requirements of Greenhouse Crops

The amount of water required is affected by the type of soil mix and the size and type of container or bed. Proper watering should provide 10% more water than is necessary so that leaching will reduce salts and good fertilizer distribution will occur. Frequent light sprinklings induce shallow rooting and may increase soluble-salt concentrations.

A simple formula for use with bench crops in order to determine the liters of water needed per square meter to thoroughly water a bench and provide 10% leaching can be determined as

$$\text{Amount of water required} = \frac{\text{Bench area}\,(\text{cm}^2) \times \text{Depth of wetting}\,(\text{cm})}{1{,}000} \tag{26}$$

A correctly designed water system will supply the amount of water needed each day of the year. The amount will depend on area to be watered, crop grown, weather conditions, time of the year, and whether a heating or ventilating system is operating. The maximum amount of irrigation water needed varies from 10 to 60 l per square meter per watering. During a hot summer dry spell, application may be needed on a daily basis. The greenhouse water system should be able to supply the total daily needs in a 6-h period, so that plants can be watered during the morning and early afternoon and the foliage has time to dry before sunset. Peak use rate is the maximum flow rate during this 6-h period. Peak use rate is needed to determine pump capacity, pipe size, type of distributing system, and storage tank size.

7.1.1 Components of Crop Water Requirements Within Greenhouses

Crop water requirement is the total amount of water that a crop needs to maintain optimal rates of crop evapotranspiration (ET_c); it is calculated as the difference between crop evapotranspiration (ET_c) and water obtained from rainfall and soil water. Technically, the water required to maintain sufficient irrigation water is the "net crop water requirement," with the "gross" crop irrigation requirement taking into account additional irrigation to consider salinity and application uniformity. In this case, crop water requirements are "net crop water requirements." Since no rainfall enters greenhouses and seasonal soil water extraction is negligible [52], because the soil is continuously close to field capacity from high-frequency drip irrigation, it can generally be assumed that the crop water requirement of greenhouse-grown crops is equivalent to crop water requirements.

7.1.2 Crop Evapotranspiration of Greenhouse Crops

The ET_c values for substrate-grown crops have been calculated by subtracting drainage from irrigation volumes. Generally, these values are similar to those for equivalent crops grown in soil [53]. Compared with equivalent vegetable crops grown outdoors with irrigation, the seasonal ET_c of greenhouse vegetable crops is appreciably lower due to the reduced evaporative demand inside the greenhouse [54]. The evaporative demand is lower inside than outside due to the decrease in penetrated solar radiation (40% on average) and the greatly reduced wind speeds of 0.1–0.3 m/s or less [55]. The evaporative demand inside the greenhouse can be 60% of that outside [56, 57].

7.1.3 Crop Evapotranspiration and Greenhouse Cooling

Whitewash (suspension of calcium carbonate) is commonly applied to the greenhouse roof and walls during warmer periods to relatively lower crop water requirement values. The whitewash reduces the amount of solar radiation entering the greenhouse and therefore also the air temperature inside the greenhouse; consequently, there is a reduction in crop evapotranspiration which is proportional to the thickness of applied whitewash. The transmissivity to solar radiation of greenhouse plastic cladding is usually about 60%; commonly used whitewash application rates reduce this to 20–30% during July.

Other cooling techniques affecting water needs for crop, such as misting and shading screens, are currently used by only a small percentage of growers [58]. Values for the reduction in radiation and consequently in crop water requirement as a function of applied whitewash are given in [56].

7.1.4 Determination of Crop Evapotranspiration for Greenhouse Crops

The FAO method estimates crop evapotranspiration ($\mathrm{ET_c}$) as the product of reference evapotranspiration ($\mathrm{ET_o}$), equivalent to the evapotranspiration of a grass crop and which quantifies the effect of climate on crop water demand, and the crop coefficient (K_c), which quantifies the effect of crop species and stage of development [45, 59].

7.1.5 Determination of Reference Evapotranspiration for Greenhouse Crops

Penman-Monteith method as a standard for estimating $\mathrm{ET_o}$ from climatic data, in both arid and humid climates, uses radiation, air temperature, atmospheric humidity, and wind velocity data. Inside plastic greenhouses, Penman-Monteith equation estimates $\mathrm{ET_o}$ compared with a standard grass crop when using a fixed value of aerodynamic resistance of 295 s/m as follows [54, 59]:

$$\mathrm{ET_O} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(0.34U_2)} \tag{27}$$

where $\mathrm{ET_O}$ reference evapotranspiration (mm/day), R_n net radiation at the crop surface (MJ/m^2/day), G soil heat flux density (MJ/m^2/day) (=0 for daily calculations), T mean daily air temperature at 2 m height (°C), U_2 wind speed at 2 m height (m/s), e_s saturation vapor pressure (kPa), e_a actual vapor pressure (kPa), $(e_s - e_a)$ saturation vapor pressure deficit (kPa), Δ slope vapor pressure curve (kPa/°C), γ psychrometric constant (kPa/°C).

FAO24 pan evaporation method estimated $\mathrm{ET_o}$ as follows [54]:

$$\mathrm{ET_O} = K_P \times E_o \tag{28}$$

where K_P pan coefficient ($K_P = 0.79$), E_o pan evaporation (mm/day)

Hargreaves equation estimated also $\mathrm{ET_o}$ as follows [53 and 59]:

$$\mathrm{ET_O} = 0.0023R_a\tau(T_{\max} - T_{\min})^{0.5}(T + 17.8) \tag{29}$$

where R_a extraterrestrial radiation (mm/day), τ ratio inside and outside solar radiation, T, $T_{\max}$ and $T_{\min}$ mean, maximum, and minimum greenhouse air temperatures, respectively.

Almeria radiation method estimated ET_o as follows [60]:

$$ET_O = (0.288 + 0.0019JD)^{R_O\tau} \quad JD \leq 220 \tag{30}$$

$$ET_O = (1.339 + 0.00288JD)^{R_O\tau} \quad JD > 220 \tag{31}$$

JD = Julian days, R_O = daily solar radiation outside the greenhouse (mm/day), τ = ratio between inside and outside solar radiation (transmissivity of greenhouse cover).

In greenhouses, solar radiation is the climatic parameter that most influences evaporative demand. Hargreaves equation and the FAO-radiation equation provide accurate estimation of ET_o. Given their limited climatic data requirements and relative simplicity (compared with the Penman-Monteith equation), these two methods are recommended for practical estimation of ET_o in plastic greenhouses under Mediterranean climatic conditions [54].

The Almeria radiation method calculates daily evapotranspiration within a greenhouse from values of the daily sum of external solar radiation and the transmissivity percentage of the greenhouse cladding. The value of transmissivity depends on greenhouse design, cover material, and management practices used to reduce greenhouse temperature during summer season [54, 55, 60, 61].

The major advantage of the Almeria radiation method is that calculation of ET_o – and consequently of irrigation requirements – considers relevant characteristics of individual greenhouses, including greenhouse construction (structure, cladding materials, age of plastic, etc.) and practical greenhouse management (whitewashing, use of shading materials, etc.). In consideration of these factors and given its simplicity and accuracy, the Almeria radiation method has been used for both extension and scientific purposes.

7.1.6 Determination of Crop Coefficient Values for Greenhouse Crops

Crop coefficient (K_c) values have been determined for the main greenhouse-grown vegetable crops. The crop coefficient values vary according to species, development stage, and crop management practices. Measured maximum crop efficient values for crops that are not vertically supported is essential. Orgaz et al. [62] suggested explanation for the relatively high maximum K_c values of supported greenhouse crops is that there is more uniform light penetration within the canopies, thereby providing relatively higher ET rates than for unsupported greenhouse crops and open field crops which tend to be shorter with denser canopies. Uniformity of light penetration increases with the following [62]: tall and open structure of the supported crops, regular pruning forming more open canopies, high leaf area indices, and high proportion of diffuse radiation inside the greenhouse.

For vegetable crops under greenhouses, planting dates and lengths of crop life cycles can vary appreciably in response to market prices, weather conditions, and farm management considerations. The standard FAO method of calculating ET_c, using three constant crop coefficient values, each for a fixed length crop stage is normally used [55, 61, 62].

Two approaches based on thermal time data have been developed to estimate K_c values during the crop development stage. For crops that are only slightly or not pruned, leaf area index (LAI) is estimated from thermal time, and K_c values are then determined from a linear relationship between K_c and LAI. For frequently pruned crops, an empirical linear relationship between K_c and thermal time has been determined for each species.

7.1.7 Irrigation Volumes Applied by Growers to Greenhouse Crops

According to [63] a survey of total irrigation volumes (crop irrigation supply) applied to vegetable crops grown in commercial greenhouses, indicated that values of annual irrigation applications are higher than the crop irrigation supply since many greenhouse growers produce two crops per year.

Values of annual irrigation applications are higher than the crop irrigation supply since many greenhouse growers produce two crops per year.

The ratio of crop irrigation supply (total volume applied to a crop) to crop water requirements is known as relative irrigation supply (RIS) and is an indicator of the adequacy of irrigation practices [64]. RIS values were determined for the main vegetable species by dividing crop irrigation supply values, determined in the survey, by crop water requirements [61]. There was very large variability in RIS values between crop species and within cropping cycles for individual crops [64].

In general, RIS values for individual crops were 2–5 during crop establishment and then progressively declined [64]. The high RIS values during crop establishment reflect the practice of applying excessive irrigation to ensure the survival and establishment of transplanted or seedlings, which initially have small root systems.

Thompson et al. [65] also compared measured crop irrigation volumes with the crop water requirements; in general, the results were similar to those reported by [64]. Thompson et al. [65] suggested that the high variability in RIS values between greenhouses with the same crop and the high values in certain parts of the crop cycles was evidence of the scope to improve irrigation practices and crop water use for soil-grown crops.

7.2 Irrigation Scheduling of Greenhouse Crops Grown in Soil

Irrigation scheduling (IS) determines the amount and frequency of irrigation based on technical criteria related to crop irrigation need. The main approaches used for IS are water balance method based on determining crop irrigation requirements from collected climatic data and use of soil moisture or plant sensors.

7.2.1 Irrigation Scheduling with Climatic Data

For greenhouse-grown crops, the calculation of crop irrigation requirement considers neither rainfall nor soil water – the latter because the soil is constantly maintained at close to field capacity. Consequently, the applied amount of a single irrigation event is equivalent to the cumulative ET_c for the period between irrigations plus additional irrigation to consider soil or water salinity and irrigation emission uniformity. For vegetable crops under greenhouse receiving high irrigation frequency, irrigation frequency is usually every day under hot temperature conditions and every 3–4 days under cooler conditions. Soil moisture sensors, in particular tensiometers, are an effective method for determining frequency.

ET_c-real is calculated from actual daily values of solar radiation and maximum and minimum daily air temperature measured inside the greenhouse for that particular day [60].

The lookup tables are effective and user-friendly tools for preparing irrigation plans for individual crops; the software is able to prepare a more tailor-made plan. In practice, such plans can be supplemented with the use of soil water sensors, such as tensiometers, to assist in determining irrigation frequencies and to adjust volumes. This combined approach (an irrigation plan based on estimated ET_c together with sensors) is an effective way to ensure optimal irrigation of greenhouse-grown crops.

7.2.2 Irrigation Scheduling with Sensors

The use of sensors to monitor soil moisture or plant water status offers the potential to irrigate in accordance with the characteristics of individual greenhouses and cropping conditions (e.g., variations in greenhouse characteristics, crop management and cycles, and soil characteristics). Additionally, these sensors offer the potential for a fine degree of crop management, such as applying controlled stresses for product quality considerations, and control of drainage for salinity or environmental management. Soil water and plant water status sensors can be used on their own as “stand-alone” methods; the two approaches can be combined; they can be used with the FAO method for estimating crop water requirements [45]; and they can be used as a supplement to irrigation management based on experience.

7.2.3 Irrigation Scheduling with Soil Water Sensors

Soil water sensors measure volumetric water content of soil ($\Theta\nu$) and soil matric potential (Ψm).

The $\Theta\nu$ is the ratio of soil volume occupied by water. The Ψm measures the force of retention of soil water by the soil matrix (particles) and indicates the availability of soil water for crops. Whereas interpretation of Ψm data for irrigation management is straightforward, interpretation of $\Theta\nu$ for practical irrigation management requires site-specific experience [66]. Soil water sensors can be read manually or with continuous automatic data collection; continuous recording allows more detailed information of the dynamics of water use by the crop and its movement in soil.

Soil water sensors can be used with different configurations depending on crop type, irrigation system, cost, and mounting of sensors on probes [66]. One sensor should be placed in the zone of maximum root concentration; additional sensors can be placed at different depths (e.g., below the roots to control drainage, to the side of the plants to control the size of wetting bulbs from drip irrigation). The most commonly used sensor configurations are one sensor within the zone of major root concentration and one sensor within the zone of major root concentration complemented by one or more deeper sensors. Irrigation management with soil water sensors is based on maintaining soil water between two limits [66]: lower limit (drier value), indication of when to start watering, and upper limit (wetter value) – indication of when to stop watering. The difference between the two limits is an indication of the volume of irrigation required. The lower limit most commonly chosen permits depletion of soil water without stressing the plant; it can also be used to impose controlled deficit irrigation. The upper limit is normally chosen to prevent excessive drainage from the root zone. It can also be reduced when controlled deficit irrigation is required. The simplest way to determine the volumes to be applied using soil water sensors is to use the selected lower and upper limits to valuate irrigation (based either on experience or on the use of the FAO method) and then to adjust the applied volumes so that irrigation is maintained within the two limits.

7.2.4 Soil Matric Potential Sensors

In non-saline conditions, soil matric potential (Ψm) is a good approximation of the total soil water potential (Ψs). In saline conditions, osmotic potential may contribute significantly to soil water potential (Ψs). The Ψm generally provides a useful measure of the availability of soil water to plants. When using Ψm, the contribution of salinity to Ψs should be considered separately [67], and equipment manufacturers have indicated the upper and lower limits based on soil water potential. These limits depend on crop species, crop developmental stage, soil texture, and the evaporative conditions.

The two types of matric potential sensors most suitable for protected horticultural crops are tensiometers and granular matrix sensors. Tensiometers are cheap, simple, and easy to use. They require preparation and proper maintenance to provide accurate and reliable data [66]. There are three types: manual tensiometers, data are obtained from the visual reading of a vacuum gauge; manual tensiometers, a switch directly activates the irrigation equipment when it reaches a predetermined value; and electric tensiometers, pressure transducers provide continuous measurement and can be used to directly activate irrigation. Granular matrix (GM) sensors measure the electrical resistance between two electrodes in a porous matrix [66, 68].

The electrical resistance between the two electrodes is a function of the soil matric potential. The water within the sensor matrix equilibrates with that of the soil. A handheld reader is used to supply the current and read the values. Data can be recorded on data loggers or input to an irrigation controller. An internal factory calibration, in the handheld reader, is used to relate measurement of electrical resistance to soil matric potential. GM sensors are cheap, simple, and easy to install and have few preparation and maintenance requirements. They have a wider measurement range than tensiometers, and they tend to be less reliable in wet soils and have a slower response in soils that dry very quickly, while they are somewhat less accurate than tensiometers but require appreciably less attention [69].

7.2.5 Irrigation Scheduling with Plant Sensors

Three kinds of plant sensors can be used for irrigation management [69]: stem diameter sensors, sap flow sensors, and sensors of leaf/crop canopy temperature.

Stem diameter sensors measure both stem contractions occurring during the day in response to transpiration and stem growth; both parameters are very sensitive to water stress. Furthermore, their sensitivity to detecting water stress in greenhouse-grown vegetable crops decreases during winter conditions of low evaporative demand [69].

Sap flow sensors that directly measure plant transpiration. They have been mostly used in research with limited use for irrigation management of horticultural crops because of their high cost and technical complexity.

The temperature difference between the leaf or the crop canopy and the environment is a sensitive indicator of plant water stress. Indicators proposed for irrigation based on this measure include the CWSI (crop water stress index).

Plant sensors have less practical application for irrigation management than soil moisture content sensors, particularly for vegetable crops.

7.2.6 General Considerations Regarding the Use of Sensors for Irrigation

When soil moisture sensors are used for irrigation management, there are two important practical considerations: replication, with a minimum of 2–3 sensors per crop, and location of the sensors, which should be representative of the crop. There are other practical considerations including cost, ease of use, preparation and maintenance requirements, technical support, ease of data interpretation, and availability of irrigation protocols [66].

In general, there is appreciably more use of soil moisture sensors for irrigation management. The most used soil moisture content sensors for irrigation management are tensiometers and capacitance sensors. Two important considerations with capacitance sensors are the cost and sensitivity of some models to changes in salinity. Tensiometers are very suitable for greenhouse vegetable crops in soil because of their low cost, simplicity, and reliability; they are not affected by salinity, and their narrow working range is not usually a limitation in greenhouse soils that generally remain moist.

7.3 Water System Components

The complete water system used in supplying water to the greenhouse consists of a pump, pressure tank, and piping. The following sections presents some details about these equipment and its selection for different systems.

7.3.1 Pump

Many types and sizes of pumps are available for supplying water. The type of pump most commonly used in greenhouse watering systems contains an impeller connected to the motor shaft. When selecting a pump to supply water to a greenhouse system, consider the capacity of water source; if the source is a pond, capacity is usually adequate for maximum use rate. If the source is a well or brook, the yield rate in m^3/h must be determined. Power required by pump to move the required flow rate is as follows:

$$\text{Pump power} = \frac{\text{Water flow rate (L/min)} \times \text{Total head required (m)}}{6.1162 \times \text{pump efficiency}}, \text{W} \qquad (32)$$

7.3.2 Commonly Used Pump Terms

Suction Head

The vertical distance from pump to water surface is measured in meter. If a well has low yield rate, water surface in the well may drop rapidly if demand is consistently great, which can affect centrifugal pump capacity by increasing suction head. Pump capacity should be matched to well yield.

If the water source is a well, the diameter of the casing will determine the equipment size that can be installed and the well's reserve capacity. Always specify a 15.24 cm or larger casing for new wells.

Pressure head: pressure required at point of delivery (m).

Friction head: pressure lost in overcoming friction between water and pipes or fitting (m).

Elevation head: vertical distance between pump and point of delivery (m).

Total head: sum of all heads against which a pump must delivery water.

Pumps should supply water under sufficient pressure to provide required flow rate and coverage. The total pressure against which a well pump must work is made up of four parts: (1) suction lift, or vertical distance water, is lifted to the pump by suction, (2) vertical distance from center line of the pump to the point where water is to be delivered, (3) required pressure at the outlet, and (4) friction in the piping system between the pump and the outlet. These values can be given in meter of water.

7.4 Fertilizer Injector

Fertilizer injector is a mechanical device that introduces concentrated fertilizer solution into the supply pipe used for crop watering. Two basic types of injectors are available. One type uses the venture principle to create a pressure difference between the fertilizer container and the water supply line, causing a flow of solution into the irrigation water. The other system uses a positive displacement pump, either water-powered or electrical, that injects fertilizer solution into the irrigation water. Each system can be adjusted to vary the ratio of solution to irrigation water.

When selecting an injector, consider the following:

System Capacity Usually rated in liters of water that can be treated per minute. Systems are available from five to several hundred liters per minute. Select a size that will handle the capacity of the distribution system.

Distribution Ratios Injectors are commonly manufactured with dilution ratios of from 1:15 to 1:2,000. The lower the ratio, the more dilute the fertilizer solution must be. Too high dilution ratio may create problems in dissolving enough fertilizer in the solution tank. A common ratio for greenhouse crops is 1:2,000.

Mobility A portable unit usually works best for an operation having individual greenhouses. The injector is moved between greenhouses when feeding is necessary. Fixed installations with piping used to carry injected water to the growing area are used in ridge furrow ranges. Where automatic watering is provided, a fixed installation for fertilizer irrigation is best.

Alternate Uses Although used primarily for fertilization, injectors can be used to apply other water-soluble materials, such as fungicides and insecticides.

7.5 Distribution Systems

In the greenhouse, two types of watering systems are in common use today: a low-pressure system operating on a water pressure of less than 7 N/cm^2 and a high-pressure system operating above 7 N/cm^2.

7.5.1 Low-Pressure System

This type of system is commonly known as trickle irrigation. Moisture is supplied to the root zone of a plant through drip tubes or soaker hoses. Water is dripped continuously or intermittently into the root zone around the plant. Soil between row crops and out of the plant area does not receive water. Although the water is applied to a small area around the plant, lateral transmission of water takes place through the root system. Major advantages of trickle irrigation are that plant foliage remains dry and water application efficiency is high.

Two methods of supplying water to this system are commonly used. One method uses an elevated mixing tank which is filled from a high-pressure water source. Water should go through a 100–200 mesh strainer before entering the tank. The tank can be any size, but a 1–2 m^3 capacity is adequate for most installations. The tank should have an opening in the top large enough to add and mix fertilizer into the water and should be elevated so that the correct pressure for the distribution system is obtained.

For the second method, the distribution system is connected to the pressure tank. A pressure reducer is placed in the line to lower the pressure to the level needed for the trickle tubes. A backflow preventer should also be used for systems that supply drinking water.

PVC pipe is most commonly used because it is inexpensive and easy to install. Gate valves should be placed at the tank and in supply lines to control water flow to various sections of greenhouse benches. Drip tubes, also known as leader or spaghetti tubes, are widely used for pot watering. This system consists of small diameter plastic capillary tubes connected to a plastic line. “Drop-in” weights are attached at the other end.

Some weights are available with a shutoff so that water flow to individual pots can be stopped when the pot is removed. The diameter and length of the tube determine its water flow rate. Tubes are available from 1 to 2 mm diameter and from 30 to 180 cm long. Low-flow porous or perforated hoses are designed for watering greenhouse benches, beds, capillary mats, outside planters, and beds. Water oozes from seams or tiny holes in the hoes under low pressure.

7.5.2 High-Pressure Systems

Fixed Spray Heads Originally developed for lawn irrigation, fixed spray heads may be used to irrigate small containers such as packs. Heads that spray water in various patterns, square full circle, partial circle, and rectangular, are available, as are stationary and pop-up heads. Sprinkler head spacing is usually 50–75% of the spray’s diameter.

Rotating Impact Sprinklers Impact sprinklers rotate slowly, about 1–2 rpm. Rotation is caused by the impact of an arm that oscillates in and out of the nozzle jet. For large areas and containers up to the 7.5 l in size, impact sprinklers are the most efficient form of irrigation. Full or partial circle sprinklers are available from a number of manufacturers to fit various pipe sizes. Interchangeable nozzles are available for all models. Some nozzles have devices (baffle or screw) to break up the spray.

Whirling rotating sprinklers spin rapidly. Rotation is caused by reaction to a jet of water discharged from the nozzles, which are attached at an offset angle on the rotating arm. Sprinklers with single or double arms for either low or high volume discharge are usable on small, closely spaced containers. These sprinklers are used mostly in greenhouses or shade structures because of small area covered by each sprinkler. Some of them discharges fine droplets of water that reduce soil splashing from the pot.

Nozzle lines may be either overhead or along the ground. Both systems are similar in that each uses a pipe with fixed nozzles placed at regular intervals. Overhead lines require rigid pipe. Either jet or fan nozzles may be used and generally are placed at 1.0 m intervals. Lines may be rotated manually automatically to apply water to different areas. Overhead nozzle lines are generally used only in greenhouses or shade structures where the pipe supports will not interfere with movement of machinery, labor, or materials.

7.6 Irrigation Water Performance Indicator (IWPI)

Characterizing water use and management in irrigated agriculture is a prerequisite for conserving agricultural water. Population growth, coupled with economic growth and increased awareness of environmental needs, is now subjecting existing freshwater resources to considerable pressures. Given that irrigation worldwide uses about two-thirds of the water diverted for various uses, there are increased societal demands for an effective accountability of irrigation water use.

7.6.1 Irrigation Water Use Efficiency (IWUE) of Greenhouse Crops

In greenhouse vegetable crops, the irrigation water-use efficiency (kg/m^3, IWUE), expressed as the ratio between marketable crop production and total crop irrigation supply, is higher than in open field crops due to the low evaporative demand inside the greenhouse that reduces water requirements and the higher productivity of greenhouse-grown crops.

In unheated plastic greenhouses, IWUE was similar between crops grown in soil and increased under the following conditions: improved greenhouse structure, increased length of growing season, and recirculation of nutrients in grown crops [63].

Performance evaluation of irrigated areas is thus an activity that is needed, not only to propose improvements in irrigation management but also for assessing the productivity of water at various scales. For each greenhouse, a set of two essential indicators for irrigation water use are calculated as follows:

Irrigation water-use efficiency can be calculated by two main methods [63]:

The Annual Irrigation Water Productivity (AIWP) Computes as Follows:

$$\mathrm{AIWP} = \frac{\text{Total value of crop productivity(kg)}}{\text{Total irrigation water consumption } (\mathrm{m}^3)},\ \mathrm{kg/m}^3 \quad (33)$$

AIWP values of greenhouse crops are generally much higher than for open field crops due to the low water use and particularly to the high economic value of vegetable crops grown out of season.

The Annual Irrigation Water Financial Return (AIWFR) Computes as Follows:

$$\mathrm{AWFR} = \frac{\text{Total value of marketing price (LE)}}{\text{Total irrigation water consumption } (\mathrm{m}^3)},\ \mathrm{LE/m}^3 \quad (34)$$

8 Conclusions

The protected horticulture crops as well as using soilless culture techniques in Egypt as well as developing countries are facing a number of important issues relating specifically to absence of local advanced modern technology, lack of the well-trained technician, limited number of qualified advisors, lack of food safety of products, and absence of advanced knowledge about crop management for soilless culture under commercial conditions. For soil-grown crops, there is no immediate solution to some, if not all these problems such as soil-borne diseases and nematode, and it is considered that the situation will not improve unless alternative solutions are considered such as using soilless culture system. In this respect, especially as most of the problems arise because the crop is in effect an intensive crop rotation, an obvious solution is to move out of the soil into some form of soilless production. There is already very little vegetable production in Egypt using soilless systems, two of the primary advantages being that they have better food safety for products and are less labor-intensive compared to conventional horticulture production.

There are many trials related to the use of soilless culture, and new technology by many Egyptian scientists is applicable to use with some vegetable crops such as cucumber, tomato, pepper, eggplant, and Chinese cabbage and potentially some ornamental crops. But, these efforts can’t compare with the new technology in developed countries such as the Netherlands and Spain. Furthermore, there is a big national project for cultivating 100,000 acres of greenhouses in Egypt during next the few years. This big number of greenhouses considers a revolution in this sector. This project needs to improve the local manufactory to produce devices, materials, and supplies for modern greenhouses. And, such big number of greenhouse will need qualified technician advisors and properly trained staff in many critical issues such as integrated pest and diseases management, irrigation, fertilization, packing, food safety issues, etc. This chapter mentioned most of the technical and scientific information needed to improve the awareness of the agriculture graduated, agriculture engineering, researcher, extension people, and investors about how to manage the greenhouse from select farm location till manage the crops inside the greenhouses with respectable scientific background.

Moreover, there is a vital need to complete this work by improving the marketing of the products via innovative way to ensure the sustainability of the greenhouse production.

Producing vegetables and ornamental from greenhouses in developing countries such as Egypt is considered as a crossroad in starting a new area of development, the main challenges related to food security (enhance the productivity) and food safety (enhance quality of products). However, the amount of fertile arable land devoted accounts for merely 55% of the total cultivated land because of urbanization. This chapter concludes that there is a vital need for improving production from greenhouses for different crops; it would be economically more efficient to produce crops based on an advanced greenhouse system, which represents profitable business with sustained supply for foreign markets. For Egypt's economy true costs are relevant, reflecting the shortage of natural resources such as land, water, and fertile soil. For the long-term strategic vision, greenhouse sector that needs better-equipped facilities to deliver sustainable production system due to crop quality improvements will gradually improve the net return per ton of production with increase quality of product. However, in conventional greenhouse system (without modern technology), the input increased over time to maintain the same output with stable product prices. This will cause higher cost per ton of production with almost the same outcome. In general, good-quality vegetable products have better prices for their products especially in the foreign markets. In addition to that, high-quality products are better for farmer's health due to the avoidance of misuse of chemical and in general create more employment opportunities. This chapter also considers a guideline book for the different stakeholders' work in greenhouse sector, the sufficient scientific background with details which can help to improve the capacity building of the greenhouse sector. We can conclude that greenhouse design, materials, facilities, and the growing system are based on many factors such as availability of water, availability of suitable land, availability of good locations, climatic factors, soil factors, etc. Select the right option of greenhouse design, constructions, growing system, and the proper crops and species depend on market capacity, market needs, availability of liquid money for establish greenhouses, availability of the experts, etc. The technical and scientific information mentioned in this chapter could help as a guide to select the suitable options for the growers and companies. We can conclude from this chapter that working in the greenhouse is a package of procedures that should be respected starting from select greenhouse location, select proper crop and species, greenhouse design, etc.

9 Recommendations

This chapter recommends many of good agricultural practices related to greenhouse sector from the beginning of select the proper site, proper water quality, proper greenhouse design, and proper management for different crops under the greenhouse by using soilless culture and conventional agriculture. This paper recommends complete package related to greenhouse management, and proper tools could be used depending on the purpose of the establishing greenhouse in particular site or location. The current work related to technical information with scientific background about greenhouse management. Additional work should be done in parallel related to the economic consideration of using different options such as selecting the greenhouse cover materials; the cost of greenhouse polyethylene cover has a big difference with the option you select such that dust-free polyethylene cover is more expensive than regular polyethylene cover by 60% or more. To decide all these options (e.g., greenhouse design, greenhouse material, using heating and cooling systems, etc.), the economic study should be done to determine the return of using each option. This chapter also draws a roadmap of greenhouse management to develop this sector. The next recommendation is the most important recommendation we can extract from the abovementioned.

1. Local small farmers can develop his own greenhouse by the use of proper and cheap greenhouse design (wooden greenhouse), select proper greenhouse cover, and improve the ventilation of the greenhouse.
2. Food safety of greenhouse products needs collaboration between the different stakeholders; the collaboration starts from the supplier of seed and rootstock that should supply resistant seed for major pest and diseases; producers should follow restricted integrated pest management program; and irrigation and fertilization program can help to make the plant more resistant for infections of pest and diseases. Finally, the farmers should know when he should spray pesticides, what is the right pesticides, and how to use pesticides.
3. Participatory approach between the European countries and Egypt for producing high-quality products; the European countries have the technology and target market with a good price, whereas Egypt has the suitable climate conditions, manpower, and production inputs. Participatory approach to transfer the technology and some high technology production inputs such as high-quality seeds and rootstocks, modern technology of greenhouses, and soilless culture systems can improve the quality and quantity of products as well as improve the vegetable and ornamental supply from Egypt to the European countries. Maybe participatory should be done in the beginning between Egyptian and European companies, and then these techniques can transfer for smaller farmers.
4. The greenhouse in Egypt during the last 20 years achieved many success related to provide the local market especially during winter season with sufficient vegetable crops such as cucumber, pepper, green beans, tomato, strawberry, and cantaloupe. Development of this sector to continue this success and increase the export volume of these crops can enhance national economy.

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