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Factors affecting greenhouse microclimate and its regulating techniques: A review

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Abstract. This paper reviews factors affecting greenhouse microclimate and its regulating techniques towards upgrading the greenhouse applications in the area of southeast China which have little or very basic technology integration. The microclimate of greenhouse is apparently influenced by the shape and its orientation, the wind direction, the property of covering material, and the use of insect-proof screen as they eventually affect the total solar radiation, the thermal characterises, and the flow pattern inside. The natural ventilation and sun block are the most common method to cool the greenhouse, but more efficient evaporative cooling such as pad-fan system, misting/fogging system and roof sprinkler are required with extreme temperatures. The earth to air heat exchanger and the heat storage using phase change material may be used for heating or cooling throughout the year which are more economic and energy-saving than other traditional thermal technologies. The reviewed knowledge provides insights into upgrading greenhouse applications in Ningbo area towards more sustainable and efficient greenhouse farming.

1. Introduction

Greenhouse technology allows farmers to grow many kinds of crops in regions and seasons of adverse climatic conditions which brings high profit. It also allows people to enjoy almost any fruit or vegetable at local market at any time regardless of whether the food is out of season. The popularity of greenhouse farming techniques increased the crop production for the whole world and contributed to the reduction of world hunger problems. However, the success of greenhouse crop productions relies on the capacity to carefully regulate the microclimate inside the greenhouse in order to meet the requirement for crop production and quality [1]. It is reported that most plants grown in greenhouse prefer an optimal temperature between 17 ℃ and 27 ℃, with extreme temperature of 10℃ and 35℃ [2] which is achieved by means of natural ventilation, shading and other cooling and heating techniques. Besides, the design parameters of greenhouse such as the shape, size, orientation, height, opening of side and roof vents, the wind direction outside the greenhouse, and the properties of covering material play an important role in influencing the microclimate of the greenhouse. This paper therefore reviews factors influencing the microclimate of the greenhouse and the latest technology for regulating the microclimate of the greenhouse, in particular, the cooling and heating techniques.

2. Factors influencing the microclimate of the greenhouse

2.1. Shape and Orientation

As mentioned, the air temperature inside of a passive greenhouse is directly dependent, besides the ambient air temperature and heat transfer confident of covering material, on the solar radiation. The solar radiation obtained by the greenhouse at a certain time and site is dependent on its shape and orientation which eventually regulate the inside air temperature with most of the direct solar radiation at being obtained at its floor which increases the air temperature inside the greenhouse. Besides, greenhouse also accepts diffusive and ground reflected radiation from roof and each wall, therefore the shape and orientation of the greenhouse have a crucial importance on the air temperature inside the greenhouse. The selection of orientation of a greenhouse (either along East-West or North-South orientations in longitudinal axis) can determine the total solar radiation received by the greenhouse , also can reduce the heating loads of the installed systems thereby saving a lot of cost. Sethi [3] compared five single span shapes of even-span, uneven-span, vinery, modified arch and Quonset type as shown in Figure 1 in terms of transmitted total solar radiation in India. Results show that uneven-span shape greenhouse receives the maximum and Quonset shape receives the minimum solar radiation during each month of the year at all latitudes. East-west orientation is the best suited for year-round greenhouse applications at all latitudes as this orientation receives greater total radiation in winter and less in summer except near the equator. Whist, Chandra et al [4] argued that north-south orientation results in better homogeneity of the microclimate for northern climatic conditions in India. While, Dragićević [5] concluded that, for uneven-span greenhouses orientated east-west and north-south (as comparison) at different latitudes at the northern hemisphere of Belgrade, Serbia, the east-west orientation of uneven-span solar greenhouse is the best suited during each month for all examined latitudes.

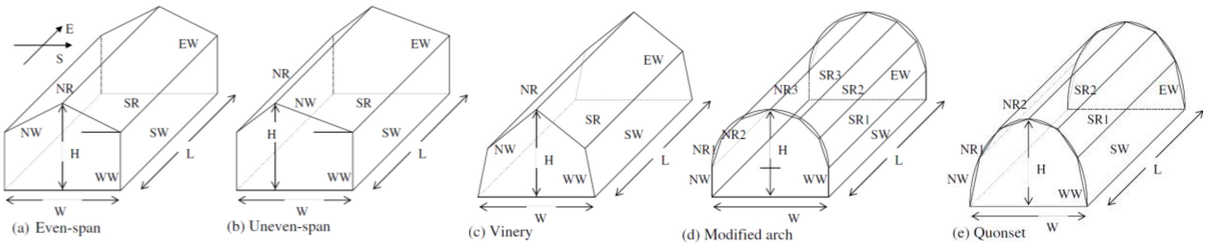

Figure 1. Greenhouse shapes in E-W orientation compared by Sethi [3]

2.2. Wind direction

The wind blows a greenhouse causing a direct positive pressure at the windward wall when the wind hits it. Whilst, the wind moves around the greenhouse and leaves the leeward wall with a negative pressure known as a sucking effect. If there are any vent openings on the windward and leeward walls of the greenhouse, fresh air will rush in the windward wall opening and exit the leeward wall opening to balance and relieve the pressures on the windward and leeward walls. The wind direction outside the greenhouse is an important factor influencing the flow of air and microclimate inside the greenhouse. Roy and Boulard [6] numerically studied the effects of wind direction on the climatic parameters inside a greenhouse which showed clearly the influence of the wind direction on the velocity, temperature and humidity distributions inside. Teitel et al. [7] found that when the wind blows perpendicularly to the greenhouse opening plane there is a cross-flow between the windward and leeward openings that results in gradients in the air and crop temperatures between windward and leeward sides. Gradients in temperature, humidity and air velocity are observed in the vertical direction as well. The temperature and humidity ratio were larger near the roof than near the crop while the air velocity was higher near the crop than near the roof. The gradients in the vertical direction were larger than those encountered in a horizontal plane in a direction parallel to the mean flow (from windward to leeward opening). The temperature difference between inside and outside and the turbulent fluxes were generally higher near the windward opening than near the leeward one. In addition, the ventilation rate increases linearly with wind speed. Khaoua et al. [8] numerically investigated the effect of wind speed and roof vent opening configuration on airflow and temperature patterns in a compartmentalised glasshouse. Results show that opening configurations combined with wind speeds strongly affect inside ventilation and microclimate parameters. Moreover, inside partition hinders the air circulation between different parts and causes significantly different internal microclimates within each compartment. Researchers also found that the wind direction affects the level of ventilation suggesting that a greenhouse with large vertical roof windows works better with a windward condition, whereas the multi-span greenhouse works better with a leeward condition [9].

2.3. Covering materials

It is important to choose suitable material for the covering of greenhouse as it will influence the radiations to plants, the diffuse light, the level of shading, and the temperature or humidity which are of concern for crop growth. Besides, factors such as the durability of material and its cost should be considered. So far, the most widely used covering are the flexible plastic films, such as polyethylene, and the rigid covering material such as plates of polycarbonate or the glass. The biggest advantages of the polyethylene are its malleability, easy installation and the cost-benefit ratio it offers in comparison with the other materials. The polycarbonate plates offer more durability and resistance to the impact, so they are often used in more extreme climates. Its main disadvantage, opposite to the polyethylene, is its high cost. Greenhouses with glass as covering material are often used in cold weather climates. They have advantages such as a total water tightness and greater insulation than simple plastic. Its principal disadvantages are its high cost in comparison with the rest, its fragility against the impacts and its high weight which needs a more resistant and adapted structure to this material. As an alternative, the use of ETFE (Ethyl Tetra Fluoro Ethylene) which is a type of plastic normally used in architecture in buildings, is starting to be studied. ETFE has high resistance to corrosion and load, supporting up to 400 times its weight. However, this material is very costly (up to 15 times more expensive than conventional plastic) and requires much more specialization in terms of the installation and structures adapted for it [10]. Montero et al. [11] suggested that diffusive films are preferred over clear films because they improve light uniformity and increase light interception by the crop. The U-V blocking films are a promising technique to reduce pest infestation. The ability of insects (whitefly and thrips) to move is associated with UV radiation; hence, by using plastic materials that absorb UV radiation, virus-disease transmission can be mitigated. Besides, they recommend multilayer rather than single-layer films since they allow addition of the positive properties of each of the components that form the film.

2.4. Insect-proof screen

In recent years crops have been grown under insect-proof screen to protect crop production from pest invasion. Greenhouses in the Mediterranean and southeastern Europe are often equipped with ventilation openings to offer good microclimate conditions for plant growth. However, these ventilation vents also serve as a port for pests to enter the greenhouse. Screens are characterized by their porosity which is the open area to its total area, their mesh size, the thread dimension, the light transmission/reflection and their resistance to airflow. In order to prevent very small pests to enter the greenhouse, screens with very fine mesh screens have to be used. However, the use of insect-roof screen would reduce the light transmission and hinder ventilation due to resistance to airflow. This is especially true duing warm and hot seasons when effective ventilation is most needed to avoid very hot and humid conditions for crop growth [11]. When insect-proof screen is used, it is important to consider the effect of screens on increasing the pressure drop on the ventilation openings which consequently reduce ventilation. The pressure drop on screens is mainly dependent on the screen porosity (ε) which can be calculated from the geometric dimensions of the screen by [11]:

$$\varepsilon = \frac{(l-d)(m-d)}{ml} \tag{1}$$

Where: l and m are the distance between the centres of the two-adjacent weft and warp threads respectively. d is the diameter of the threads. The temperature difference between greenhouse and ambient air with screens (ΔT_{sw}) and without screens (ΔT_w) can be related to the porosity of the screens by below correlation:

$$\Delta T_{sw} = \Delta T_w(5 - 4\varepsilon) \tag{2}$$

It should be borne in mind that equation 2 only give a rough estimate of the ΔT_{sw} as the temperature difference with and without a screen depends on greenhouse type, crops, weather etc. Considering the drawback of utilizing insect-proof screen, it is suggested that the ventilation openings are uncovered when there is no risk of pest invasion [12]. In addition to the effects on the ventilation rate, the screens reduce light transmission into the greenhouse by creating strips of shadow on the crop when they are installed on roof openings. In dusty regions the shadow effect may be worsen due to the accumulation of dust on the screens [11].

3. Greenhouse regulating technologies

3.1. Natural ventilation

Natural ventilation is a common way to cool the crop area in summer as it removes heat inside the greenhouse by a pressure difference created by wind and temperature. Besides temperature control, greenhouse ventilation also serves the imperative functions of humidity control, CO_2/oxygen replacement and air circulation. Sase [13] suggested that under the condition of a mild climate, proper design and good control of natural ventilation can ensure effective cooling and uniformity of the microclimate inside the greenhouse. Omer [14] investigated various designs of low energy greenhouse and stated that various change such as the size and shape of the vents can improve air movement over crops. Von Zabeltitz suggested that, if local wind speed is high enough, the volume to floor ratio of the greenhouse should be as large as possible to maintain favourable environment for crop growth. The side vents can be as large as possible, but roof vent opening should not be too large to avoid rain entering the greenhouse during the rainy season. The American Society of Agricultural and Biological Engineers (ASABE) standards [15] recommended that in tropical conditions the total sidewall vent area and the total ridge vent area should be the same with at least 15-20% of the floor area of the greenhouse. Other researchers reported different ratios of ventilation area to the surface roof area that were optimum to their specific applications. Those ratios reported are summarized in Table 1.

Table 1. Different ratios of ventilation area to the surface roof area reported by researchers

Researchers	Year	Ratio of vent to surface roof area	Conditions
(ASABE) standards [15]	2003	15-20%	Tropical conditions
Connellan [16]	2000	20%	Higher temperature regions
Kamaruddin et al. [17]	2000	40%	Tropical regions
Montero et al. [18]	2001	33%	-
Albright [19]	2002	10%	-
Campen [20]	2005	40.4%	Under Indonesian conditions
Hermanto et al. [21]	2006	60%	In humid tropics

Simone [22] argued that it is difficult to recommend the exact vent size for ideal ventilation. Generally, more smaller vents are better than one large one with the total venting area equal to about 1/6 the area of the south facing glazing. It is recommended to have at least one low vent and at least one high vent so that hot air will rise up and exit the upper vent(s) and draw fresh cooler air into the lower vents. Also, the vents should be positioned in a way which will prevent cold air from flowing directly across the plants.

In addition to natural ventilation, Artificial ventilation using induced draught and exhaust fans, blowers, helps in maintaining a greenhouse temperature closer to ambient due to higher rate of air change than that could be achieved through natural ventilation. In most greenhouse applications, fan induced ventilation is employed together with evaporative cooling system thus leading to pad-fan systems [23].

3.2. Pad-fan system

Mechanical cooling (for example, refrigeration-type air conditioning) is possible, but seldom affordable or practical for commercial greenhouses. Evaporative cooling techniques using pads & fans, fogs, mists, sprinklers can be very effective and affordable when used properly [24]. Evaporative cooling is a process that reduces air temperature by evaporation of water into the airstream. As water evaporates, energy is lost from the air causing its temperature to drop. Evaporative cooling is one of the most effective cooling method for controlling the temperature and humidity inside a greenhouse.

As shown in Figure 2a, pad-fan system applies a combination of evaporative pads and extractor fans to hermetic greenhouses. In this method, one of the walls is replaced with a wet pad, and there are fans on the opposite side wall to intake the air. The pad-fan system has a greater air saturation efficiency than that of the fog system which is also cheaper and less consumable in water and energy. But the method only works well with hermetic greenhouse structures which facilitates all incoming air passes through the evaporative pads on the side wall with powerful extractor fans being installed on the opposite wall to provide the suction effects [25].

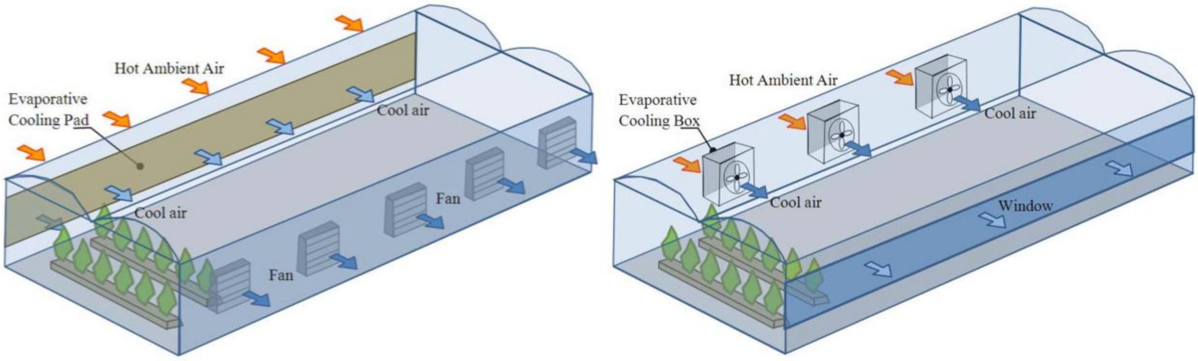

Figure 2. (a) Pad-fan evaporative cooling and (b) Evaporative cooling boxes (after Franco, 2014)

In addition to the pad-fan systems, the evaporative cooling boxes (Figure 2b) provide an alternative system which consist of an evaporative cooling unit with a cooling chamber, usually equipped with a plastic packing of a honeycomb mesh in order to allow air to come into contact with the water. The unit has a pump for water recycling and a fan for impelling the cooled air horizontally into the greenhouse. Evaporative cooling boxes do not require extremely hermetic structure of the greenhouse as the fan is an integral part of the cooling unit which impels the cool air into the greenhouse [25]. It worth mentioning that the suitability of evaporative cooling is restricted to particular region and climate. E.g. it is not suited to humid tropics due to high humidity levels.

3.3. Misting/fogging Systems

Greenhouse Misting Systems or fogging systems allow greenhouse temperatures to be reduced and humidity levels increased providing a growing environment for crops. The cooling is achieved by evaporation of small droplets of spraying water. The advantage of mist and fog systems over wet pad systems is the uniformity of conditions throughout the greenhouse, therefore eliminating the need for forced ventilation and airtight enclosure. Li and Willits [26] compared the cooling performance of a low-pressure (405 kPa) and a high-pressure fogging system (6.89 MPa) in two empty naturally ventilated greenhouses under summer conditions. The experiments showed that the evaporation efficiency of high-pressure system was at least 64% higher than the low-pressure system, however, the cooling efficiencies of the high-pressure system were only 28% higher than that of the low-pressure system. Katsoulas et.al. [27] suggested that mists, fogs, and sprinkler systems can be used with or without mechanical ventilation, but they still require controlled air exchange to maintain the correct humidity/air temperature balance.

3.4. Roof Sprinkler Cooling system

Roof Sprinkler Cooling systems provide cooling by sprinkling of water on the roof surface of greenhouse to form a thin layer of free water surface which evaporates and cools the surface. These systems are simple, and appear to be effective, but are not suited in areas where water is in short supply. Cohen et al. [28] carried an experimental comparison of evaporative cooling in a naturally ventilated glasshouse due to wetting the outer roof and inner crop soil surfaces. It was found in the glasshouse with a growing tomato crop, temperature differences between the air inside and outside of the glasshouse were affected by the wetting treatments. With growing plants, or wet soil surfaces, evaporative cooling of the roof surface appeared to have a minor effect on glasshouse air and foliage temperatures. These temperatures, however, were strongly affected by evaporative cooling of soil and foliage surfaces. Direct evaporation of a water droplet suspended in a spray mist in the air appeared to be the most effective site for evaporative cooling of the glasshouse.

3.5. Apply sun block
One of the best ways to avoid heat accumulation in the greenhouse is to block some of the solar energy from getting inside in the first place though this would also block light for photosynthesis. However, it can often seek a balance between the need for sufficient light for plant growth and the need to control potentially damaging temperatures by blocking, filtering, and reflecting incoming light on the outside of the greenhouse covering, or by using fixed or retractable shade materials inside the greenhouse. Plants are adapted for varying light levels and most species reach their maximum photosynthetic efficiency at rather low light intensities relative to full sunshine. Extremely high light levels can actually stop or slow down photosynthesis which directly reduces the available carbon dioxide required for photosynthesis. Therefore, providing some shade can often be beneficial (20-75% depending upon the species and the light intensity), resulting in a net gain in photosynthesis and continued healthy plant growth [24].

3.6. Earth to air heat exchangers (EAHES)
An earth-to-air heat exchanger draws air through buried ducts or tubes for cooling the greenhouse in summer and heating in winter. As the temperature of the ground below 3 meters is practically constant it therefore provides space conditioning throughout the year, with the incoming air being heated in the winter and cooled in the summer by means of earth coupling. Systems can be driven by natural stack ventilation, but usually require mechanical ventilation. As a new sustainable development technology, the greenhouse earth to air heat exchanger is more economic and energy-saving than other traditional thermal technologies for greenhouse because of the high heat capacity of the shallow soil. The technique is suited to greenhouse with a moderate cooling demand, located in climates with a large temperature differential between summer and winter, and between day and night.

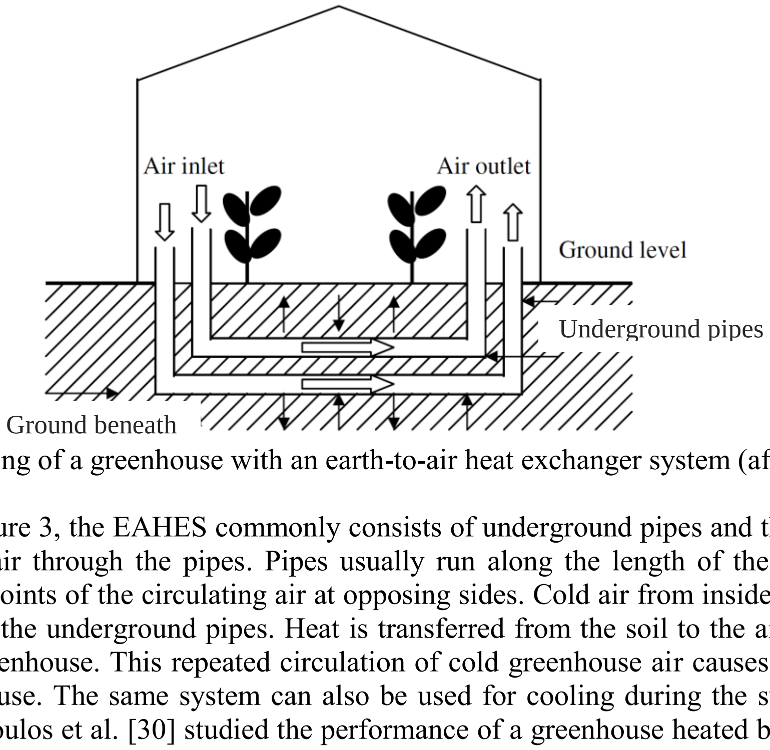

Figure 3 Coupling of a greenhouse with an earth-to-air heat exchanger system (after Sethi, 2008)

As depicted in Figure 3, the EAHES commonly consists of underground pipes and the airflow system, which forces the air through the pipes. Pipes usually run along the length of the greenhouse, with entrance and exit points of the circulating air at opposing sides. Cold air from inside the greenhouse is circulated through the underground pipes. Heat is transferred from the soil to the air stream and then returned to the greenhouse. This repeated circulation of cold greenhouse air causes the heating effect inside the greenhouse. The same system can also be used for cooling during the summer conditions [29]. Mavroyanopoulos et al. [30] studied the performance of a greenhouse heated by an earth-air heat exchanger consisting of 20 aluminium pipes with 15m length, 0.2m in diameter and 0.2mm thickness installed at a depth of 2m in a greenhouse of floor area 150 m^2. The greenhouse air temperature was adjusted by blowing the greenhouse air through the pipe system whenever the air temperature dropped below 12°C or exceeded 28°C. This resulted in a minimum mean night air temperature of 8.1°C inside the greenhouse with an absolute minimum of 7°C while the outside minimum mean and absolute minimum air temperatures were −0.8°C and −3.0°C, respectively, during the same period.

3.7. Phase change material storage

Due to the high cost of energy in greenhouse, the storage of heat is important for a greenhouse to provide optimum inside conditions during winter months. The strategy of passive heating system of greenhouse is to reduce the heat losses and at the same time to transfer excess heat from inside the greenhouse during the day to heat storage. This heat is used during the night to satisfy the heating needs of the greenhouse [31]. Besides other heating system such as water storage, rock bad storage, mulching, movable insulation, thermal curtain and earth to air heat exchanger, the use of phase change materials (PCM) is a promising alternative method. PCM are substances with a high latent heat which is capable of storing and releasing large amounts of energy when melting and solidifying at a certain temperature. In the heat storage cycle, PCM can store large amounts of heat in melting from solid to liquid at a constant temperature (phase transition temperature). In heat dissipation cycle, a circulating fluid air or water can extract heat from the storage unit causing the phase change material to solidify. Berroug et al. [31] developed a numerical thermal model to analyze the thermal performance of a greenhouse with a north wall made with the phase change material of $CaCl_2 \cdot 6H_2O$ as a storage medium. Results shows that with an equivalent to 32.4 kg of PCM per square meter of the greenhouse ground surface area, temperature of plants and inside air were found to be 6–12°C more at night time in winter period with less fluctuations. Relative humidity was found to be on average 10–15% lower at night time. Caprara et al. [32] compared a traditional sensible heat storage system of water tank storing unit with a latent heat storing unit based on PCMs. It was proven that PCMs materials are much more suitable for low temperature applications than sensible heat storing materials (water). In addition, PCMs unit shows a better response to the hourly energy fluctuations of solar collectors and greenhouse demand than water tank unit. Due to the limit of the paper, a more detailed review in terms of other heating technologies for agricultural greenhouse can be referred to the work of Sethi et al. [29].

4. Conclusions

The design parameters and the selection of microclimate control techniques are vital for sustainable greenhouse farming in the regions of adverse climatic conditions. This paper therefore reviewed the factors influencing the microclimate of the greenhouse and the latest advance in technology for regulating the microclimate of the greenhouse. The influence of greenhouse design parameters and its functional characteristics on microclimate of greenhouse was reviewed in terms of its shapes and orientations, the wind direction, the selection of covering materials and the effects of insect-proof screen. The importance of natural ventilation was stressed and the recommend location of opening vents and the ratio of ventilation area/surface roof area were summarized. The performance of evaporative cooling including pad-fan system, misting/fogging system and roof sprinkler system was discussed. The advantages of earth to air heat exchanger and the heat storage method using phase change material were introduced which can be used for heating or cooling throughout the year. The above knowledge offers insights for the design and selection of regulating techniques for advancing greenhouse applications in southeast China's Ningbo area with low technology structures. In the future, we will carry out further comparison and investigation of the reviewed microclimate regulating techniques to find out suitable solutions for local greenhouse farming.

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