# Chapter 5
# Greenhouse Structures

Greenhouses have to provide optimal climate conditions for the plants growing inside. They have to protect plants against too low temperatures, wind, rain, hail, birds, and insects (Waaijenberg 2006). The following components are very important for successful greenhouse design: shape, orientation, structure, cladding material, foundation, ventilation, and technical equipment for climate control.

Structures for protected cultivation can be classified into greenhouses and net or shade houses mostly used in tropical regions.

*Shade and net houses* have water-permeable cladding nets. They shade the plants and protect them from incoming insects if roof and side walls are completely covered by nets, and if the mesh is small enough. They reduce too high radiation, wind speed and the impact of heavy rain, but they do not protect the plants from being wet by precipitation. Fertilizer will be washed out much more easily, and controlled fertigation is not possible. They have no positive effect on water-use efficiency.

*Greenhouses* have cladding material that is impermeable to water and has high transmittance for natural light. Greenhouses protect the crops from rain and other climate factors described in Chaps. 2 and 4. Usually, the cladding material is plastic film in mild climates and glass or rigid plastic in temperate climates.

The width of one span depends on the available width of plastic film if the roof is covered by the film in a longitudinal direction, which is the recommended approach. The width of available cladding material is limited in many countries by the manufacturing process. The necessary width of plastic film for the roof on multi-span structures, depending on the width of the span, is:

| Width of span (m) | Minimum width of plastic film (m) |
|---|---|
| 5 | 6 |
| 6 | 8 |
| 8 | 10 |

The shape of the construction, the height to the eave and ridge (the whole volume), the cladding material, and the number of spans influence internal climate conditions such as temperature, humidity, light transmittance, and $CO_2$ buffer.

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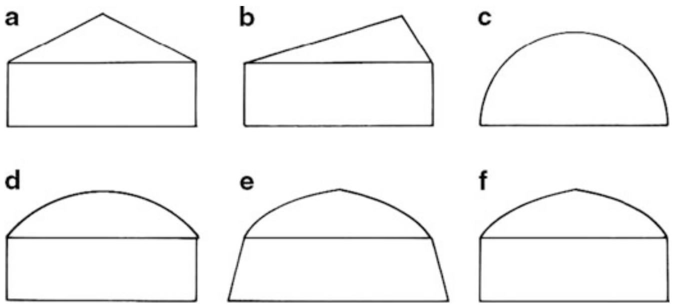



**Fig. 5.1** Most frequent shapes of greenhouses: see text

The most frequent shapes for greenhouses (see Fig. 5.1) are saddle roof (*a*), saw tooth or shed roof (*b*), round arched tunnel (*c*), round arch with vertical side wall (*d*), pointed arch with sloping side wall (*e*) and pointed arch with vertical side wall (*f*). Preferable for plastic film greenhouses are designs (*e*) and (*f*).

Single-span and multi-span greenhouse can be distinguished.

Ventilation efficiency by natural ventilation, which is proportional to pressure differences (Bot 1983), depends on the height of the greenhouse if ventilation openings are positioned at the ridge and the side wall. The higher the ridge and the bigger the distance between ventilators at ridge and side wall, the higher are the pressure differences. On the other hand, wind loads and the strength of the structural components depend on the greenhouse height, just as the heat requirement depends on surface area. High greenhouses with large volumes provide better climatic conditions, but also increase the heat requirement if heating is needed.

The design of the greenhouse has to be chosen according to the climate conditions and the general design requirements, and not to national traditions.

*Simple low-cost greenhouse structures* (Fig. 5.2) allow the economic development of regions in development countries, but usually they have more unfavourable climate conditions, with higher temperature and humidity followed by lower yield, higher pest infestation and a higher amount of non-marketable crop.

Simple plastic film greenhouses predominate in warmer subtropical countries (De Pascale and Maggio 2005). Crops cannot be grown all year round, and the yield does not fulfil quality standards completely, because of inadequate climate conditions inside the simple greenhouse structures (Baille 1999b, 2001). The structure and the shape are often not adapted to the climate conditions of the region in development countries. Low-cost plastic film greenhouses in particular are designed on the principle of minimum capital and technological input as well as low running costs. Sophisticated greenhouses often are too expensive. The aim is to find a compromise between suitable greenhouse technology, increasing costs, and economical output for the grower.

Greenhouse crop production in warmer climates requires a specific design of greenhouse structures and climate control equipment. There is a need for higher


**Fig. 5.2** Cheap low-cost structures

technological standards to face the increasing competition by products and marketing from other countries (Pardossi et al. 2004).

*Cost-effective greenhouse structures* with higher investment in height of the structure, volume and better ventilation efficiency need less expense for spraying and provide better quality, healthier crop and better yield. They may have a better cost–benefit ratio and permit environmentally friendly production (Fig. 5.3).

Plastic film greenhouses and glass greenhouses are being built side by side in Turkey. Growers and scientists are still discussing the advantages and disadvantages of glass and plastic film greenhouses for Mediterranean climates. Many growers are still building glass greenhouses, supposed to have less maintenance and better light transmittance. The light transmittance of plastic film greenhouses should be higher because of less construction components if the greenhouses are cleaned regularly (see Chap. 6).

One important point of crop production in greenhouses should be "the sustainable development that meets the needs of the current generation without undermining the ability for future generations to meet their needs" (De Pascale et al. 2005).

The environmental compatibility of plastic film greenhouses is higher than that for glass greenhouses. This can be investigated by the life cycle assessment method (Sect. 5.8).


**Fig. 5.3** More cost-effective greenhouses

## 5.1 Round Arched Tunnel Greenhouses

The *round arched tunnel* greenhouses are still the most used greenhouses in many developing countries with mild climates (Fig. 5.4).

The *advantage* of the single-span tunnels is the relatively simple construction system and the wind resistance if they have foundations and if the steel tubes are not too weak, but the disadvantages are not negligible with reference to yield and quality.

The *disadvantages* of the round arched tunnel greenhouses are**:**

- The net greenhouse floor area fit for plant cultivation is small compared to the ground occupied by the tunnels. The space left between two tunnels is 1–3 m (Fig. 5.4).
- The plastic-film consumption is higher per net floor area.
- The surface area, and as a result the heat consumption, is higher in heated greenhouses.
- The greenhouse volume is too small for appropriate climate control.
- There is a relatively wide nearly horizontal zone, 1–2 m wide, at the top where condensation drops fall down from the covering material.
- 6–30 wires are stretched in longitudinal direction. The plastic film can be damaged by the wires, which are fastened to the bent pipes. Water droplets cannot run off along the inner surface of the film even if No-Drop films are used

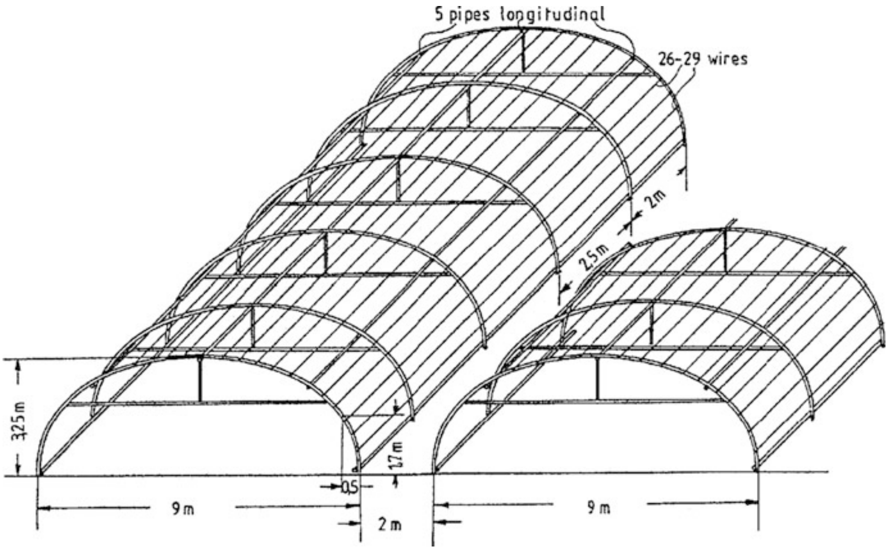



**Fig. 5.4** Round-arched tunnel greenhouse

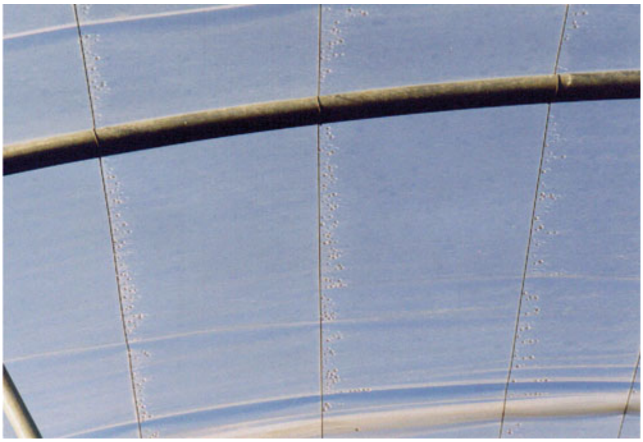


**Fig. 5.5** Drop condensation at wires

(Fig. 5.5). The droplets drop down where the wires touch the film. Thus, wires should be avoided in greenhouse construction.

- When tall plants (tomatoes, cucumbers, and roses) are grown, the arched design of the wall causes about 1 m of ground to be not usable between the sidewall and the first row on each side (Fig. 5.6).

**Fig. 5.6** Free space at bent side wall

**Fig. 5.7** The border effect

- The plants near the sidewall ventilation and near the gable grow less than those in the middle of the tunnels. This border effect (Fig. 5.7) is caused by lower temperatures, by lower humidity next to the vents and gables, and by wind effects.
- Very often, round arched tunnels are built without any foundation or the foundations are not sufficiently secured against uplift wind forces. They will be destroyed by uplift wind force (Fig. 5.8).
- *Ventilation* efficiency is not sufficient if only the overlapping plastic film and the doors at the gables are "opened". This kind of ventilation cannot be operated mechanically, but each opening has to be opened manually. This takes a long time, and the greenhouses can be overheated in the morning (Fig. 5.9).

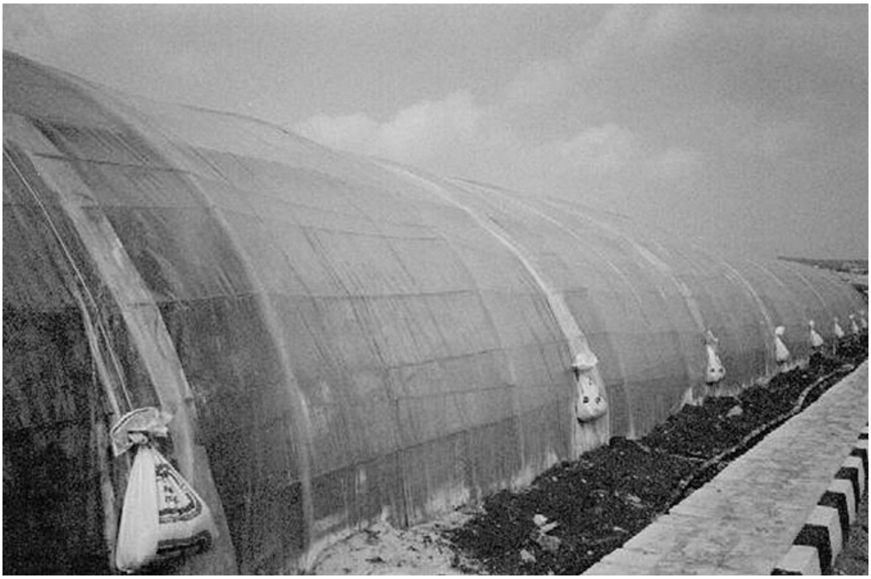


**Fig. 5.8** Greenhouses without foundations are secured against uplift forces by sand sacks (Jordan). Point foundations are preferable

The simple ventilation of round-arched tunnels by opening the overlapping film sheets is not sufficient. If the film has a width of 6.5 m, there is an opening every 6 m at the sidewall. The ratio of vent area to greenhouse floor area becomes less than 10%. For optimum ventilation, the ratio should be more than 20% (Chap. 9).

Even if the vent openings are opened by parting the overlapping film sheets over the whole round-arched surface, the ventilation efficiency is not always sufficient (Fig. 5.10).

If round arched tunnel greenhouses are supposed to be built, then only with *through ventilation openings* at both side walls — but the border effect has to be taken into consideration (Fig. 5.11).

## *5.1.1 Improvements for Tunnel Greenhouses*

The disadvantages of single-span tunnel greenhouses can be reduced by some improvements such as

- Sufficient stability resulting from the dimensions of the construction, sufficient fixed connections of the components, and using foundations.
- Pointed arched construction to avoid drop fall at the top of the roof.
- Installation of additional straight side walls with through ventilation openings.

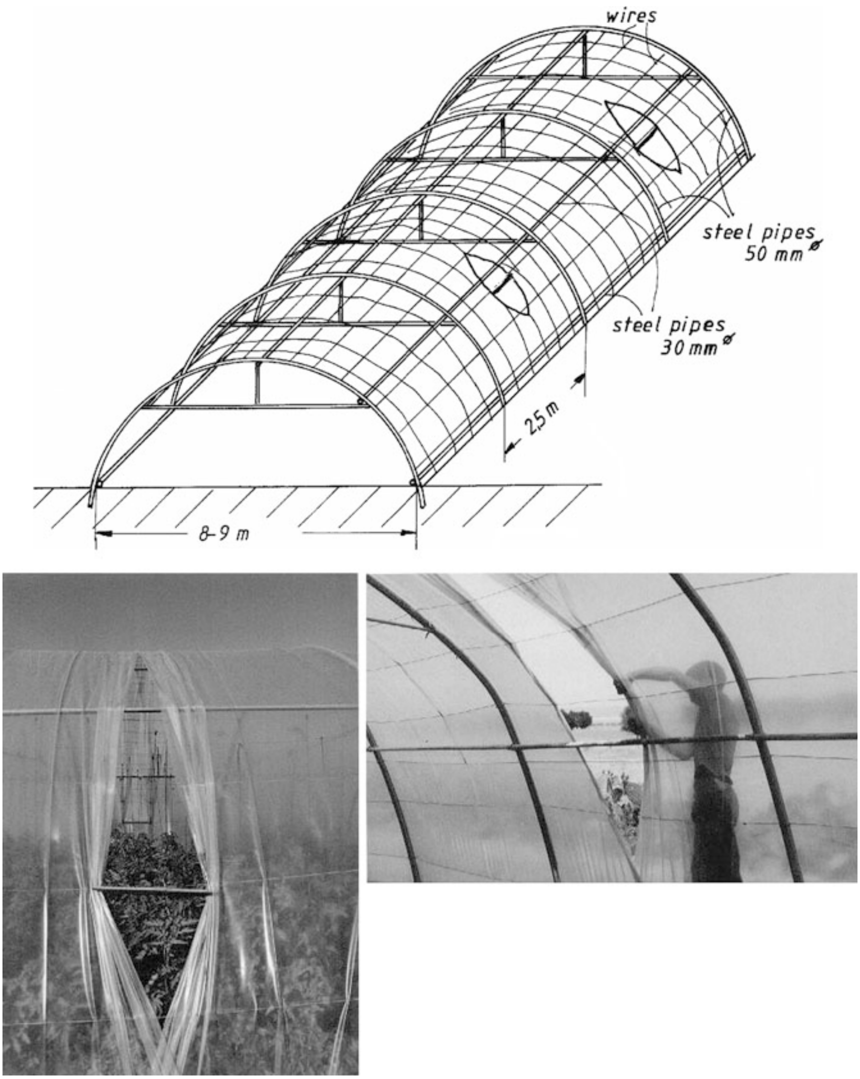



**Fig. 5.9** Inefficient ventilation

## *5.1.2 Dimensions*

The dimensions of the construction are responsible for the stability of the greenhouse. Figure 5.12 shows some dimensions of steel tubes for a simple single-span tunnel greenhouse from experience sufficient for normal wind loads in mild climates. But point foundations have to be installed. These dimensions can be used if no standards are available.

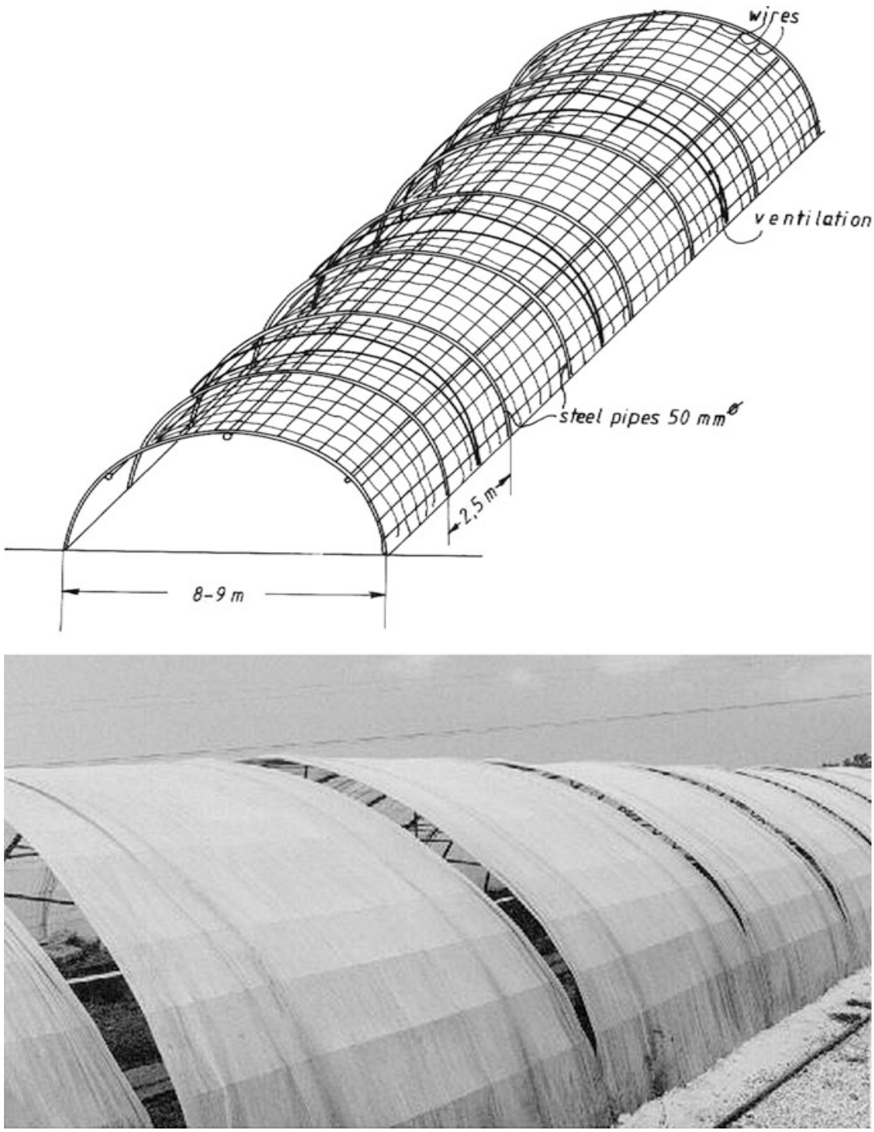



**Fig. 5.10** Ventilation by parting the overlapping film over the whole arch is not sufficient

Waaijenberg (1990), Waaijenberg and Denkov (1992) has made calculations in accordance with the climate conditions of Tunisia and with a crop load of 0.15 kN/$m^2$. Figure 5.13 shows a structure with horizontal trellis girders and another one with extra bracings (Von Zabeltitz 1999). The arch tubes, combined with trellis girders and extra bracings, can be designed using tubes with dimensions

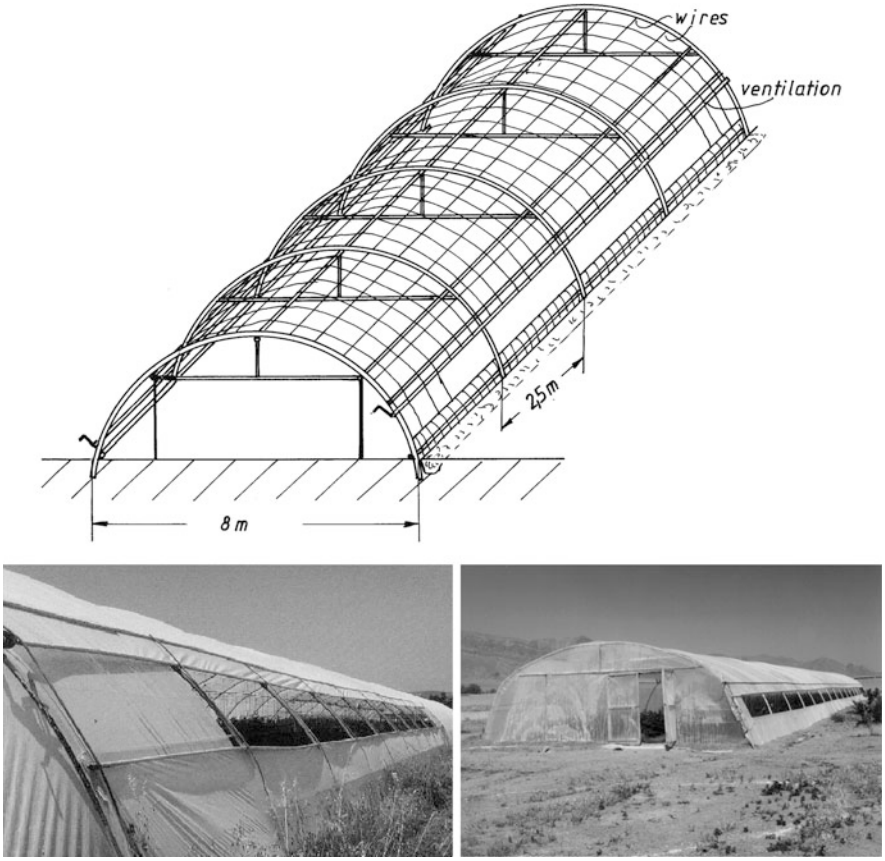



**Fig. 5.11** Through ventilation at both sides.

48.3 × 2.9 mm even if the arch distance is 2.0 m. The same figure shows the dimensions of a bitunnel, calculated also with crop load.

### *5.1.3 Pointed Arched Construction*

The round arched tunnel normally has a wider more or less horizontal zone at the ridge. Water drops fall down even when using special No-Drop film. The steel tube arches of the tunnel greenhouses are frequently made of four parts (1–4 in Fig. 5.14a). If the upper bends *2* and *3* are turned and fixed at the ridge by a new connector, the result is a more pointed arched roof built with the same construction components (Fig. 5.14b). If a more distinct pointed arch is desired, the lower bends *1* and *4* can be kept and new bends *5* and *6* can be installed at the ridge with a corresponding connector (Fig. 5.14c).

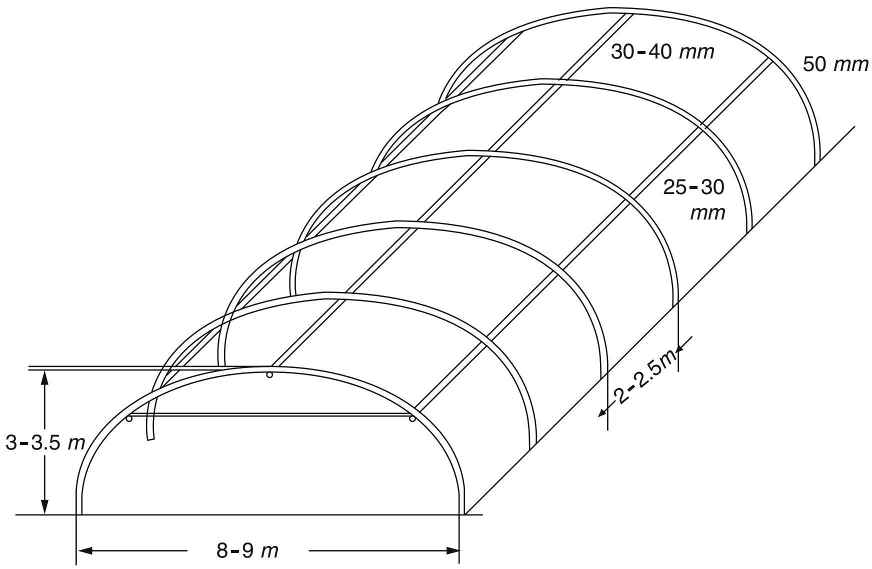



**Fig. 5.12** Some dimensions of a single-span round-arched tunnel.

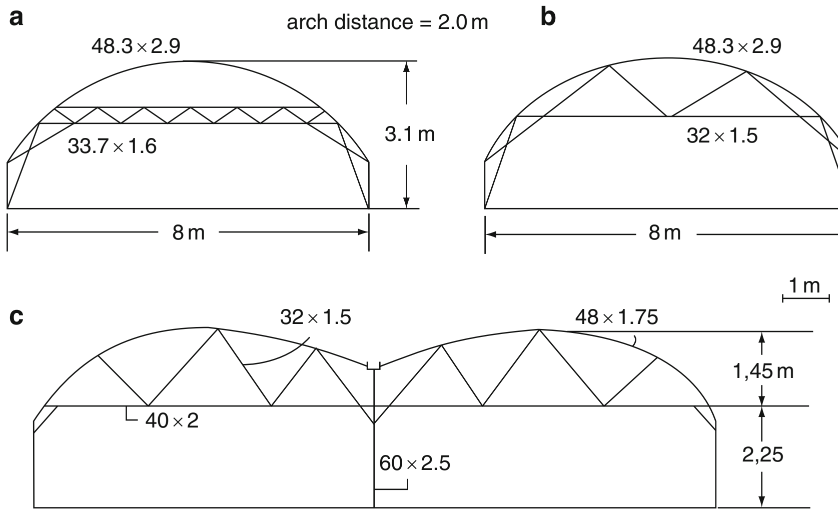



**Fig. 5.13** Single-span and Bitunnel designed according to European standard EN 13031-1 (2001).

## *5.1.4 Enlarged Tunnel Greenhouse*

If farmers can not remove the traditional round arched greenhouses and build appropriate ones, they can improve the existing greenhouses as shown in Fig. 5.15 for better climate control. The height of the greenhouse can be enlarged

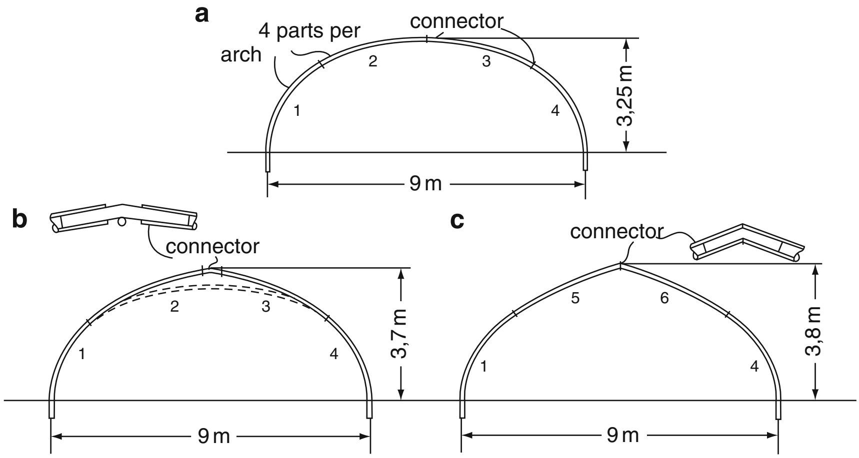



**Fig. 5.14** Modification of round-arch to pointed-arch tunnel.

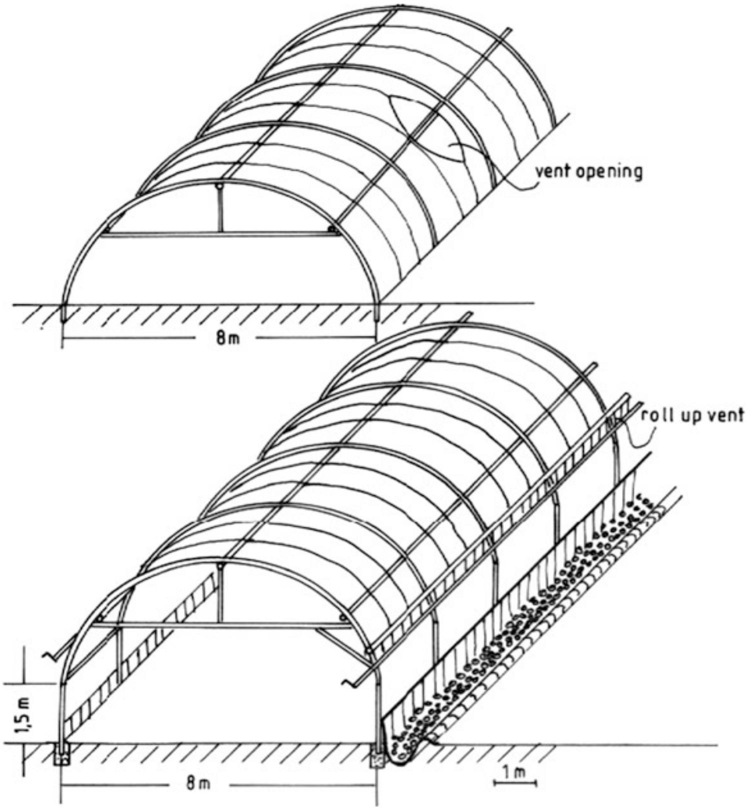



**Fig. 5.15** Improvement of existing round-arched greenhouses by installing vertical side walls

by connecting pipes of about 1.5 m length, fixed to the ends of the original truss tubes. In this case, concrete point foundations are absolutely necessary. Through side-wall ventilation has to be installed. The film below the ventilation openings is buried into the soil and filled with gravel. In this way, it works as a gutter to drain off rainwater, and it gives additional stability to the whole construction against uplift wind forces.

## 5.2 Multi-Span Greenhouses

Multi-span gutter-connected plastic-film greenhouses fulfil most of the design criteria. They have advantages as follows:

- The greenhouse volume is larger, and the climatic conditions are better during day and night. The sidewalls should be as high as possible. A sidewall height of 3 m is favourable, but wind resistance has to be guaranteed.
- Ventilation with sidewall and gable ventilators can prove sufficiently efficient, if the total width of the multi span unit is limited to about 18 m.
- Ventilators can be operated mechanically.
- Crop density is higher, and the border effect is less influential. Vertical sidewalls avoid losses of space along the sidewalls and allow the use of machines to work inside the greenhouse.
- The usable greenhouse area per ground is higher.
- Pointed-arched roofs can be built in order to reduce dripping.

According to the prevailing climate conditions, multi-span greenhouses should have roof or ridge ventilation, if the mean maximum outside temperature exceeds 27°C.

But one has to take into consideration that roof or ridge ventilation is very costly. The investment for these ventilation systems represents 25–30% of the whole investment for the greenhouses. The following investment costs for greenhouse structures including plastic film are given in €/m$^2$ floor area (Castilla and Hernandez 2007):

| | Without roof vents | With roof vents |
|---|---|---|
| Sicily | 10–16 | 27 |
| Greece | 11 | 14.8 |

Small units with two to three spans only can therefore be built with side-wall and gable ventilation only if the gutter height is 3 m or more. Roof or ridge ventilation has to be built for multi-span greenhouses with four or more spans. Many greenhouses in the subtropics do not have ridge vents, but one has to take into consideration that the vent openings have to be enlarged if insect screens ought to be used (see Chap. 10).

Figure 5.16 shows a pointed arched steel tube construction with 5 m width of span and gutter height of 2 m only. Pointed-arched or gothic-arched structures have

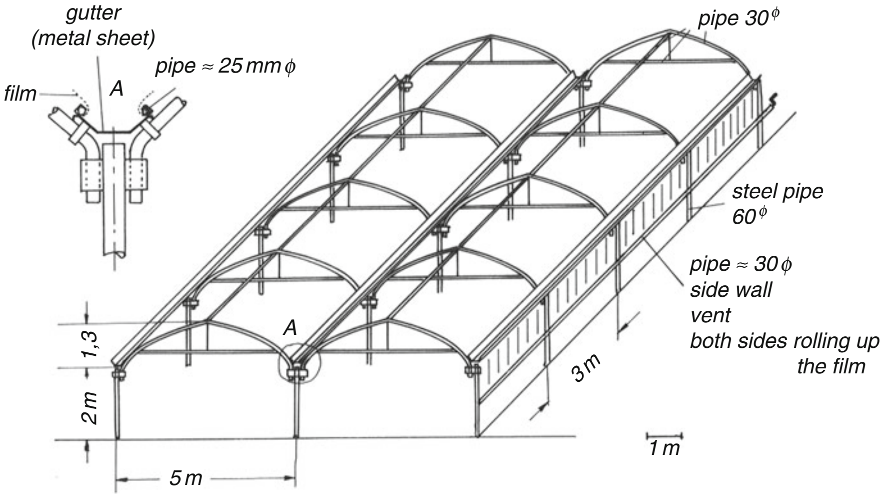



**Fig. 5.16** Pointed-arched greenhouse

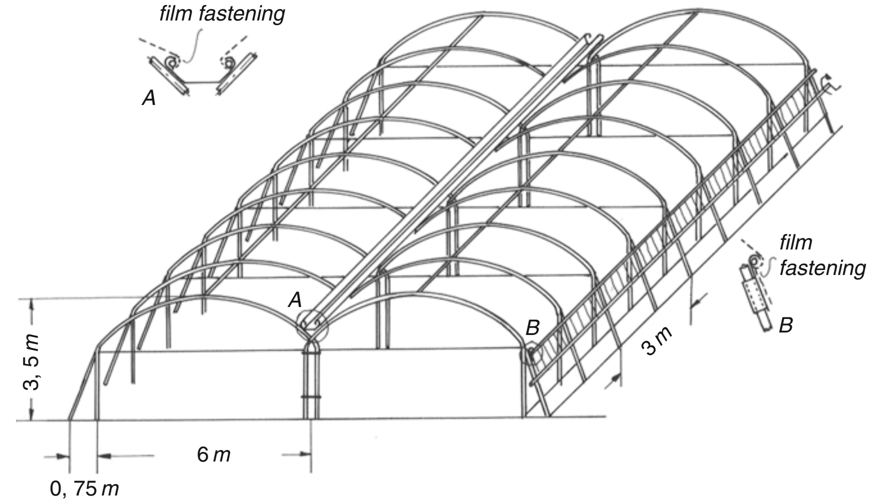



**Fig. 5.17** Round-arched greenhouse with sloped side walls

advantages over round-arched structures, because condensation water can flow off better on the inner side of the film, and therefore little water drops down on the plants (see Sect. 7.4). The side wall should be 3 m or more. The plastic film at the gutter is fixed and stretched by rolling it up on a steel tube in the gutter. The roof tubes are fixed at the stanchions by clamps in which they are inserted and screwed. The width of the single span depends on the maximum width of the plastic film available in the country.

Figure 5.17 shows a round-arched gutter-connected construction with a sloped side wall to stabilise the construction against wind forces. The plastic film is fixed and stretched by rolling it up on a tube in the gutter profile as shown in *A*. The fastening and stretching of the film at the side wall without gutter can be done also by rolling it up on a tube. Both films the roof and the side wall cladding are rolled on one tube as shown in section *B*. The film is rolled up on the sloping side wall for ventilation. Round-arched constructions may be easier to design, but pointed-arched constructions are preferable for plastic film.

Sloped side walls have advantages if insect screens are installed, because ventilators with insect screens need bigger opening areas for sufficient ventilation efficiency (Fig. 5.18) (also see Chap. 10).

Figure 5.19 shows the possibility of fastening the plastic film by rolling it up on a steel tube. Both the plastic film at the side-wall ventilation as well as the plastic film of the roof can be fixed by rolling up on one tube.

Figs. 5.20–5.22 is show some more examples for multi-span greenhouses.

Various roof or ridge ventilations are possible if the greenhouse units have more than two spans and if the total width is more than 18–20 m (Figs. 5.23–5.25) (see Chap. 9).

Figure 5.26 shows two kinds of roof ventilation. Both open one half of the roof. Design *A* is linked at the gutter and opens at the ridge. This ventilation has to have good resistance against perpendicular wind forces, and has to be installed tightly. Design *B* opens at the gutter and is linked at the ridge. Both ventilations should open a minimum of 1 m. This means that a sufficiently long and strong rack-and-pinion drive have to be installed.

All those multi-span greenhouses can have a pointed-arched roof, which has advantages for the run-off of condensation water.

At the side wall, there is a plastic film fastened to the posts and dug into the soil on the other edge. The film in soil is filled with gravel, and thus acts as a gutter. In addition to that, it stabilises the whole structure against uplift forces

**Fig. 5.18** Sloped side walls covered with insect screens and rolling-up ventilation in Jordan

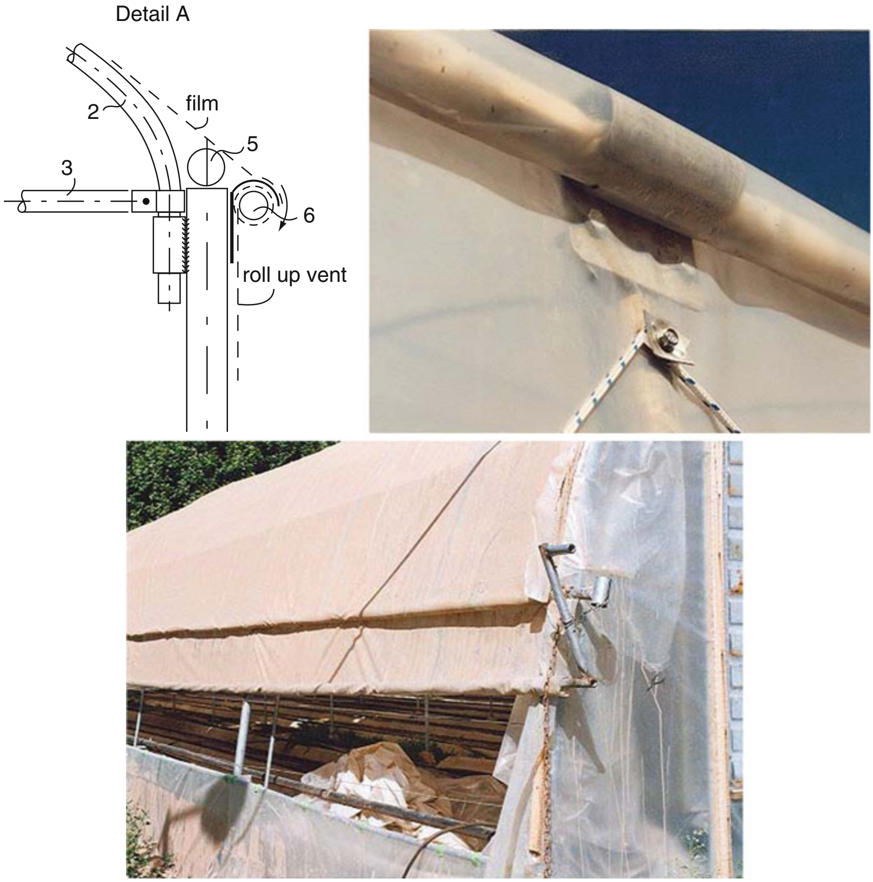
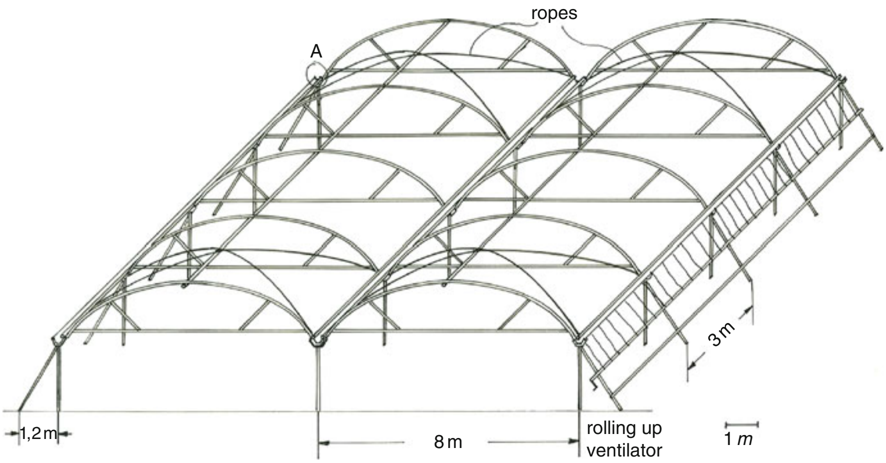



**Fig. 5.19** Fixing and stretching both the plastic film of the roof and the ventilation opening on one tube

If greenhouses do not have a gutter at the eave of the side wall, they have to have ditches deep enough to drain off the rainwater. The plastic film at the side wall has to be dug a minimum of 20–30 cm into the soil to prevent water from penetrating the greenhouse from the side wall.

A recommendable solution is shown in Fig. 5.27. The plastic film of the side wall forms a ditch of 30–40 cm depth. The ditch is filled with gravel of 10–30 mm diameter. As a result of this, rainwater can drain off; the side wall is tight against penetrating water, and the dug plastic film gives additional stability to the construction.

Greenhouses have to have a sufficient slope in longitudinal direction to drain off rainwater by gutters or ditches.



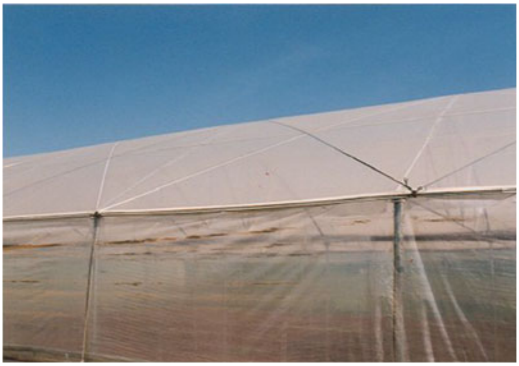



**Fig. 5.20** The additional stretching of ropes across the roof at the gable ends may have advantages in areas with high wind speed (Iran)

If the farmer has chosen a greenhouse construction, he has to observe the *mounting and installation* very carefully. Even if the construction principally fulfils the requirements and specifications, mistakes during the mounting can weaken the whole construction and can make the investment useless.

After the construction is ready for operation, the farmer has to take care of *continuous maintenance* so that the greenhouse can be operated as long as possible.

Stable connection of the steel components by clamps is very important for the wind resistance of the greenhouse construction (see Sect. 8.2).

*The clamps must not slide on the tubes but have to be tightened firmly*. After the mounting has been finished, one has to check whether all clamps, screws, and bolts are screwed and firmly fixed.

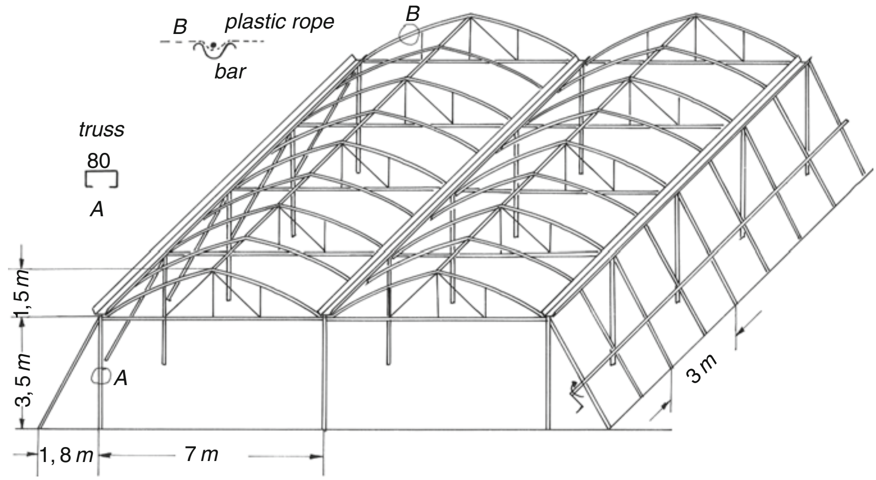



**Fig. 5.21** Pointed-arched multi-span greenhouse with sloped side wall and gutter height of 3.5 m (Israel)

## 5.3 Greenhouses for Tropical Lowlands

Greenhouses are very important for tropical regions because they avoid the disadvantages of open-air production and increase the yield and quality remarkably (Figs. 5.28–5.30).

Average yields for tomatoes in tropical countries (Malawi, Seychelles, Thailand) are:

| | |
|---|---|
| Open field in dry season | 6 kg/m$^2$ |
| Open field in wet season | 2–3 kg/m$^2$ |
| Protected cultivation | 10–15 kg/m$^2$ |

Average commercial yields of tomatoes (long cycle from September to May) in Almeria, Spain, are 14 kg/m$^2$ (Castilla and Hernandez 2005), and the commercial yields of cherry truss tomatoes in South Spain are 8.5–11.9 kg/m$^2$ for one season (Hita et al. 2007).

The available cost-effective construction materials and the available width of the plastic film vary in different countries. Design materials for greenhouses are wooden poles, timber profiles and steel tubes depending on the available materials in the country. The dimensions of the greenhouse spans are restricted by the available dimensions of materials and plastic film.

The design also varies from simple structures for small-scale farmers to more industrialised multi-span structures for large-scale farmers. Small-scale farms are in the majority in many developing countries. Therefore, appropriate cost-effective structures have to be designed.

**Fig. 5.22** Multi-span pointed-arched greenhouses with flap ventilation in Turkey. Thermal screen and hydroponic system inside

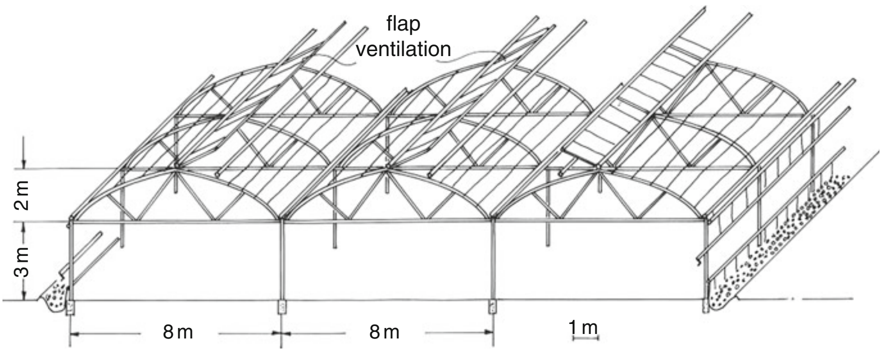



**Fig. 5.23** Multi-span greenhouse with flap ventilation at ridge and roll-up ventilation at side wall

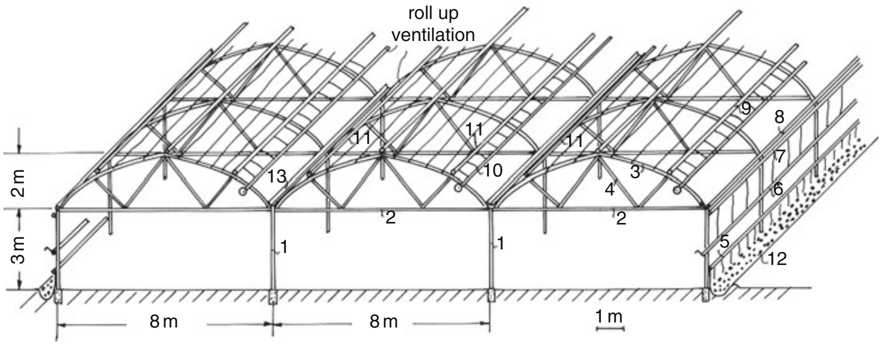



**Fig. 5.24** Multi-span greenhouse with roll-up ventilation at roof and gutter. A good holder is necessary at the gutter to close the vent opening tightly and to prevent fluttering by wind forces

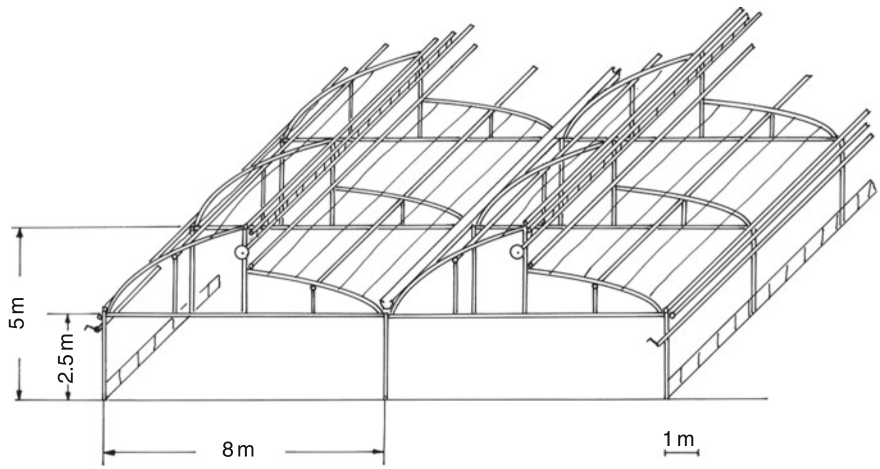



**Fig. 5.25** Vertical roll-up ventilation at the ridge, which is very effective in hot climates

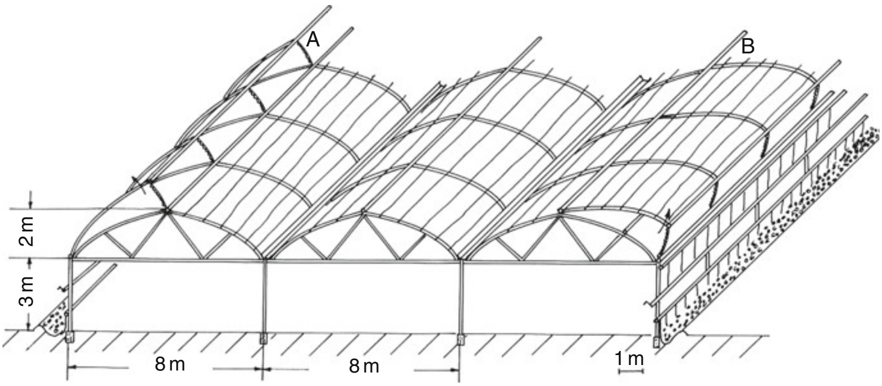



**Fig. 5.26** Multi-span greenhouse with roof ventilation linked to gutter and ridge

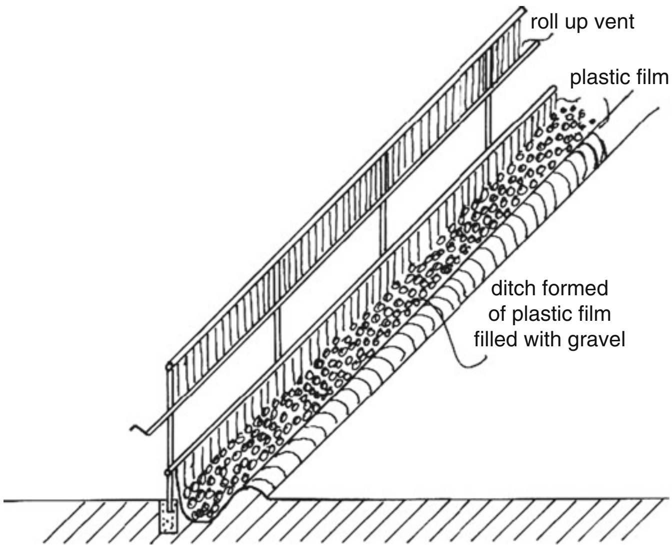



**Fig. 5.27** Ditch as gutter

**Fig. 5.28** An open-air tomato crop destroyed by a heavy tropical rain shower (Seychelles)

One can find different greenhouse types:

- For short duration of life, structures designed of wood, with untreated poles and without foundations. The duration of life is only 3–5 years.
- For longer duration of life, structures designed of treated timber profiles or steel tubes. Those structures need more investment for the structure itself, but they are more cost-effective and economical in the long term.

**Fig. 5.29** Comparison of a pepper crop in the open air and under a shelter structure, both planted on the same day in the Seychelles

The general requirements for greenhouse structures, depending on the climate conditions, are described in Chap. 4.

Greenhouses for tropical lowlands should have the following characteristics (Von Zabeltitz 2000):

- Crop protection from rain, wind, and too high global radiation. Cladding material impermeable to rain. UV-stabilised plastic film with long duration of life is sufficient for most of the tropical lowland greenhouses.
- Crop protection from birds and insects.
- Ventilation openings should be equipped with insect screens if necessary, but ventilation efficiency should not be influenced too much (Chap. 10).
- Very efficient ventilation. Ventilation openings at side walls and the ridge. Ridge ventilation is absolutely necessary.
- The relation of greenhouse volume to ground floor area should be as large as possible. The gutter height should be about 3 m minimum.

The higher the structure, with ridge vents, the higher the ventilation efficiency by the chimney effect.

- Gutters are necessary to drain off the rainwater and to prevent the rainwater from penetrating the greenhouse.
- The roof at the gutter should overlap the side wall to avoid the penetrating of sloping rainfall.
- Resistance of the construction for wind and crop loads.
- Foundation construction should guarantee wind resistance and prevent stanchions from rottenness.

Net houses with screens as roof cover are not suitable for sustainable production.

The ridge ventilation systems of the structures (*a*) to (*d*) in Fig. 5.31 have got better ventilation efficiency than structure (*e*). The wind blows straight through the two openings at the ridge in structure (*e*). One vertical opening at the ridge causes a better air exchange through the whole structure by suction and pressure forces (chimney effect). Growers in India are going to build vents with one opening at the ridge like (*d*), but with alternate directions of the openings to improve the ventilation efficiency (see Chap. 9). If the roof construction is made of steel tubes, a

**Fig. 5.30** A tomato crop in the open air and under a very simple shelter structure in Malawi. The protected crop has higher yield and better quality, even when the simple structure does not fulfil the mentioned characteristics

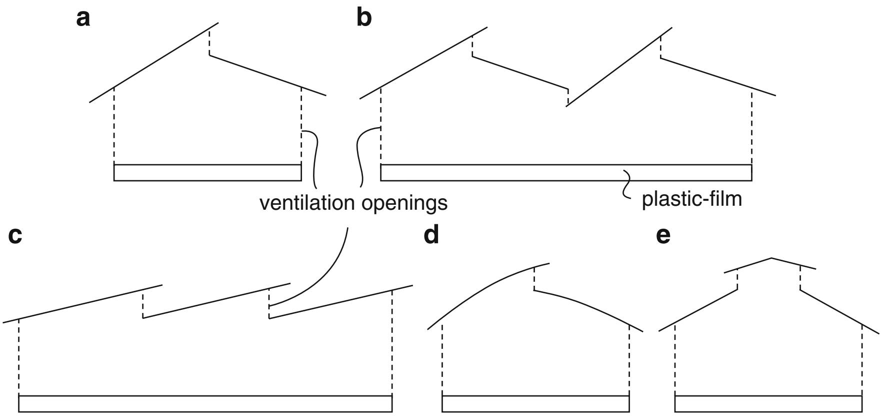



**Fig. 5.31** Some principal shapes for tropical greenhouses. All of them have ridge or roof ventilation. The side walls and gables are open in warm and humid tropical climates. They have to be closed at night in tropical highlands

round- or pointed-arched structure like (*d*) is recommendable, because the plastic film can be stretched better over curved constructions.

A 50–60 cm-high plastic film should be fixed near the soil at side walls and gables. That way, rainwater and small animals can not penetrate into the greenhouse. The plastic film can be dug into the soil and fixed to the structure using stretched wires, timber profiles or steel tubes.

A simulated comparison of greenhouse structures for conditions in Indonesia similar to types (*d*) and (*e*) in Fig. 5.31 gave no significant differences in mean air temperatures inside the greenhouse (Hemming et al. 2006a).

But our own measurements in single-span greenhouses in the Seychelles indicated significantly higher temperatures in the daytime in a greenhouse type like (*e*) compared to type (*d*). The temperature difference at a global radiation of 4 $kWh/m^2$ was 3.5°C (Von Zabeltitz 1994) Figs. 5.32–5.42 show examples and discussions for tropical greenhouse.

Gutters of plastic film only, which are sometimes used, are not recommendable because water pockets occur very easily (Figs. 5.34–5.41, Tables 5.2 and 5.3).

Figure 5.42 shows a comparison of two trusses manufactured in India. The round-arched commercial truss is connected together by clamps, and designed for high wind speeds. The width of the span is 9 m and the truss distance is 3.84 m. The second truss with straight side wall is a welded structure designed by a farmer in India. The dimensions of the components are given in Tables 5.4 and 5.5.

The material costs of the bent truss were 6,140 Indian Rupees for galvanised steel and 4,418 Indian Rupees for mild steel.

The material costs for the welded truss was 1,358 Indian Rupees for mild steel. That means only 30% of the cost of the bent truss, but more than 20 welds were necessary to connect the truss.

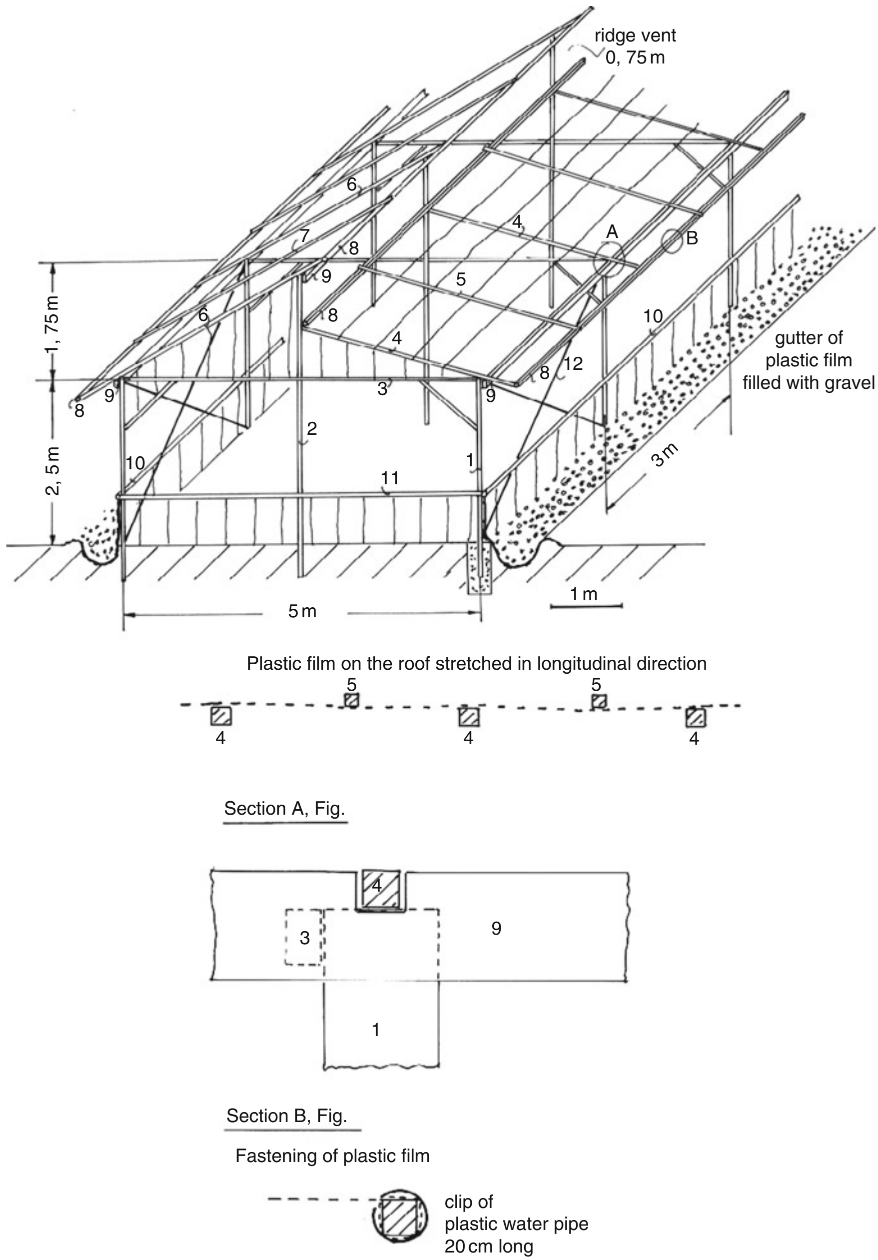



**Fig. 5.32** A design for small-scale farmers similar to that called Kenya type in Africa (Von Zabeltitz 1998; Pauer 2002). The vertical stanchions (*1*) and (*2*) are round poles which are dug directly into the soil or which should be put into concrete foundations for the extension of duration of life. All other components are rectangular timber profiles. The numbers in the drawing signify the profiles, and their dimensions are given in Table 5.1. The width of the span is limited by the width of available plastic film. The details show how the plastic film is fixed

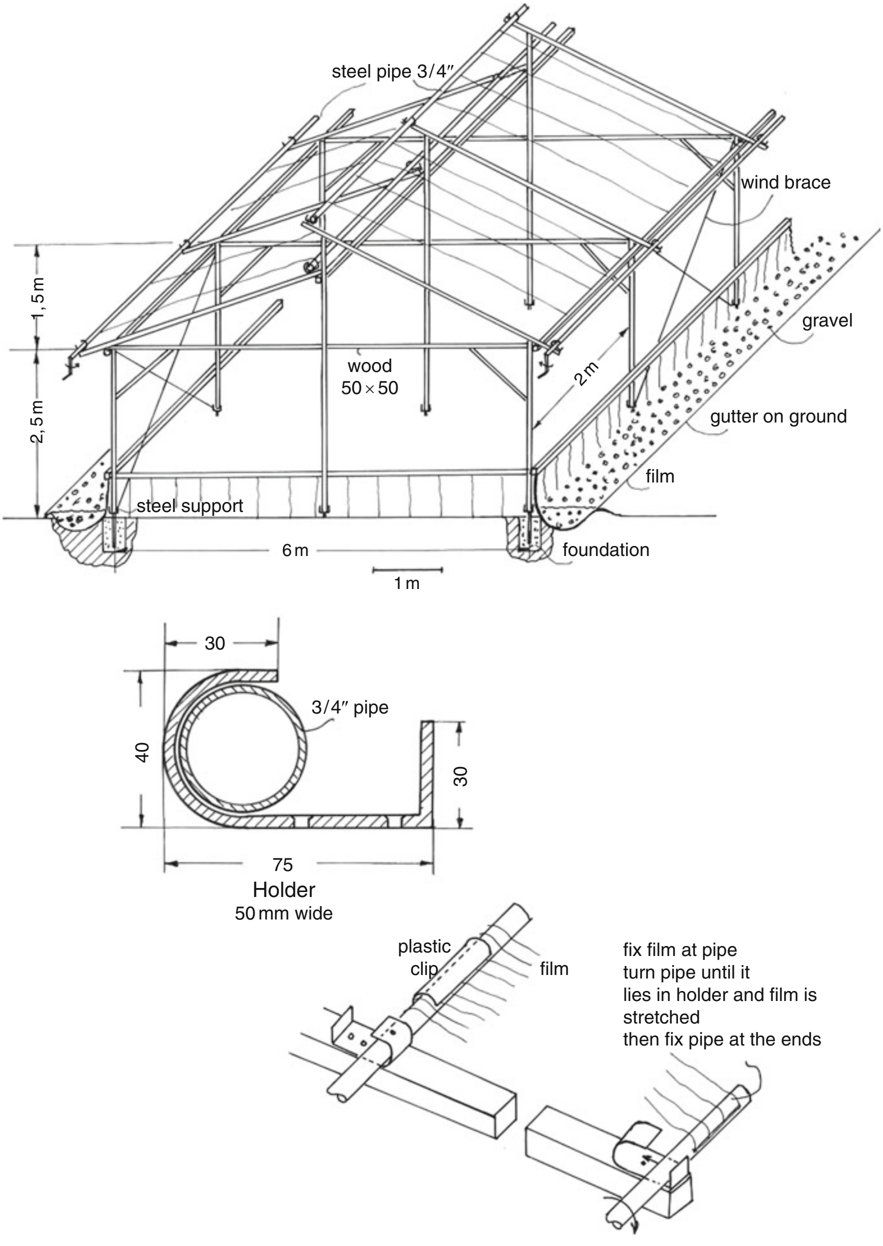



**Fig. 5.33** An improved saddle-roof structure, where the plastic film is fixed and stretched on the roof by rolling it up on steel tubes positioned in holders. The plastic film can be replaced more easily and tightened again in hot seasons

**Table 5.1** Dimensions of the components for the construction in Fig. 5.32

| Designation | Cross section (mm) | Length (m) |
|---|---|---|
| 1. Pole | 150 Ø | 3.0 |
| 2. Pole | 150 Ø | 5.0 |
| 3. Timber | 76 × 50 | 5.0 |
| 4 Timber | 50 × 50 | 3.25 |
| 5. Timber | 40 × 40 | 3.5 |
| 6. Timber | 50 × 50 | 4.0 |
| 7. Timber | 40 × 40 | 4.25 |
| 8. Timber | 40 × 40 | |
| 9. Timber | 76 × 50 | |
| 10. Timber | 40 × 40 | |
| 11. Timber | 40 × 40 | 5.0 |
| 12. Wire for wind brace | | |

The costs were calculated in Indian Rupees (year 2000) for galvanised and non-galvanized steel according to Indian standard IS 1239 OF (1990), as well as for non-standardised, non-galvanised steel.

The total price of 6,140 Rupees for the galvanised structure is 1.4 times more than the non-galvanised structure of standardised profiles, and 3.1 times more than the mild steel structure of non-standardised profiles. Non-galvanised (mild) steel profiles must be painted very carefully a minimum of three times to prevent rust. In this case, the duration of life can be similar to galvanised steel. Galvanised steel profiles should never be welded together.

Some important recommendations for tropical greenhouses are (Mutwiwa et al. 2007):

- Large ventilation openings with more than 60% opening related to floor area covered by insect screens to block insect entry physically and optically (see Chaps. 9 and 10).
- Spectrally modified cladding material, to reduce heat load by blocking NIR transmittance (Sect. 7.3).
- UV blocking material to reduce pest population.
- A forced extraction ventilation when temperatures exceed the permissible maximum.

## 5.4 Greenhouses for Tropical Highlands and Subtropics

The greenhouses for tropical highlands and for subtropics have to have lockable ventilators that should close very tight without leaks to prevent heat loss during cold nights. Very efficient ventilation for hot periods is a prerequisite for good climate control. Greenhouses for tropical highlands should have ridge vents for natural ventilation, although they are relatively expensive. Greenhouses for the subtropics do not have ridge or roof ventilation very often. In this case, the width of the

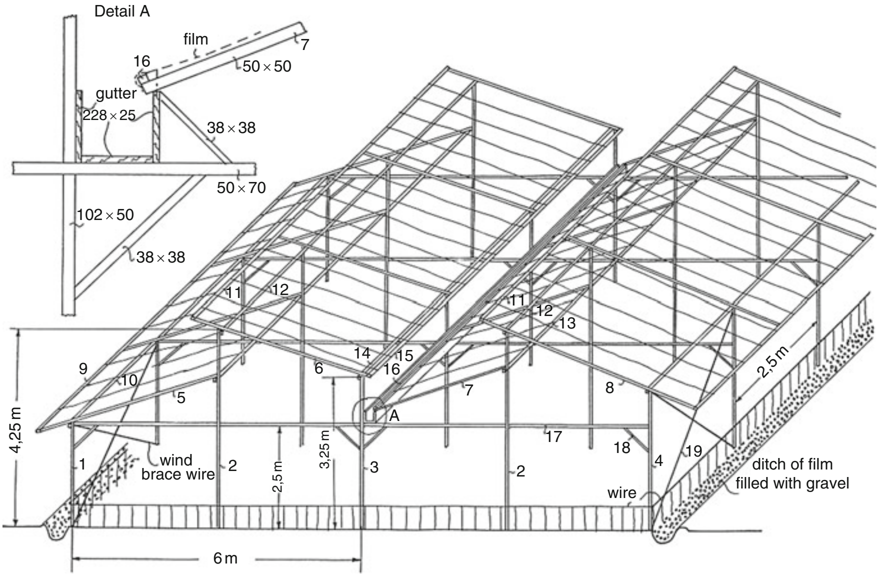



**Fig. 5.34** A design for a double- or multi-span timber structure for the Seychelles, where imported timber profiles from South Africa were the cheapest available materials in the country, much cheaper than inland timber and steel tubes. Even the gutter is made of timber. The inner side of the gutter is lined with plastic film dimensions are given in Tables 5.2

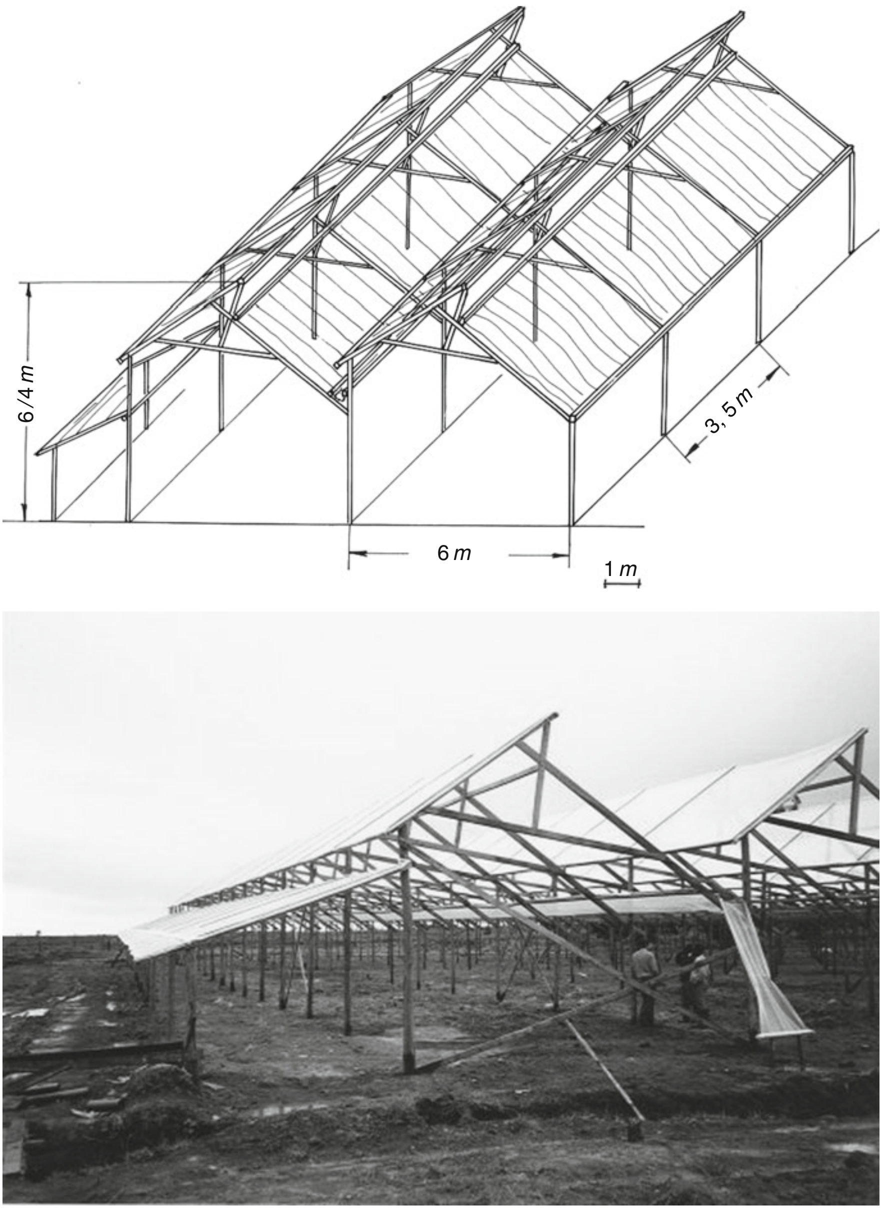



**Fig. 5.35** Wooden structure from Kenya: 6.4 m ridge height, high volume and a canopy for rain protection on the weather side. The plastic film gutter is not advisable because of getting water pockets. The canopy at the side wall against sloping rain fall is highly recommendable

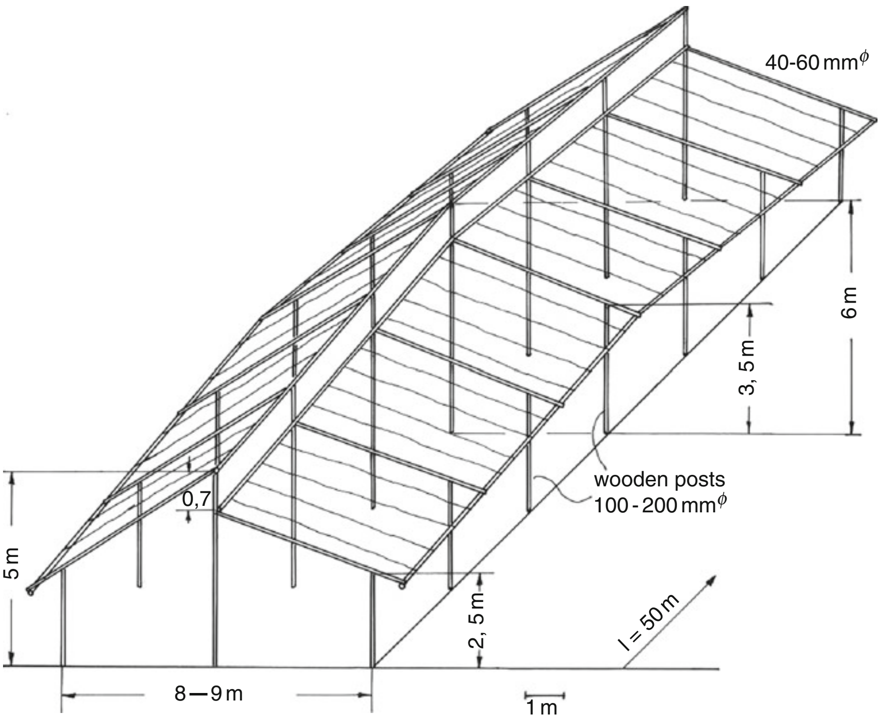



**Fig. 5.36** Wooden structure in Colombia with a roof slope in longitudinal direction to lead off rainwater

**Fig. 5.37** Greenhouse for roses in Malawi with open space only in the roof and gable area, to protect the flowers from wind and sloping rainfall

multi-span greenhouse units should be limited to guarantee sufficient ventilation by side-wall and gable vents only (see Chap. 9). Greenhouses in the USA have forced ventilation by fans because of cheap electricity.

**Fig. 5.38** Steel tube structure in Thailand with 5 m gutter height, ridge ventilation and nets against birds

Gutters for rainwater collection are necessary for rainy seasons. The cladding material should be opaque to long-wave radiation because of heat loss at night (see Chap. 7). The plastic film should have No-Drop properties to avoid drop condensation and dripping (see Sect. 7.4). Ventilation openings should be designed with regard to the installation of insect screens (see Chap. 10) and energy-saving measures considered if heating is necessary in the subtropics. The design criteria are given in Chap. 4.

Various greenhouse types are available, from simple wooden structures to highly developed steel tube and aluminium structures with all equipment for climate control and energy-saving methods. One can observe that the height of greenhouses

**Fig. 5.39** Steel tube greenhouse on farm in Bangalore, India, covered with insect screens. The ridge vents at the gable ends have alternate opening directions for better ventilation efficiency

is increasing with increasing state of the art and knowledge about efficient climate control, but the investment costs are also increasing (Figs. 5.43–5.56, Tables 5.6–5.10).

## 5.5 Greenhouse Constructions for Arid Regions

Greenhouses for arid regions have to protect crops from excessively high irradiation, too low temperatures in winter, wind, sandstorms, and too low humidity. Usually, they have forced ventilation by fans in combination with evaporative cooling (see Chap. 11). A heating system is necessary for cold nights with frost (see Chap. 12). The cladding material is shaded by outside nets for flower production in many cases. Permanent outside shading is less suitable for vegetable cropping in the main winter season. Moveable shading systems inside or outside have advantages for light control, in the early morning for example. Moveable inside shading can be used as thermal screens to reduce heat losses in winter. Shading systems are also necessary to reduce incoming radiation and to improve the cooling efficiency (Figs. 5.57–5.63).

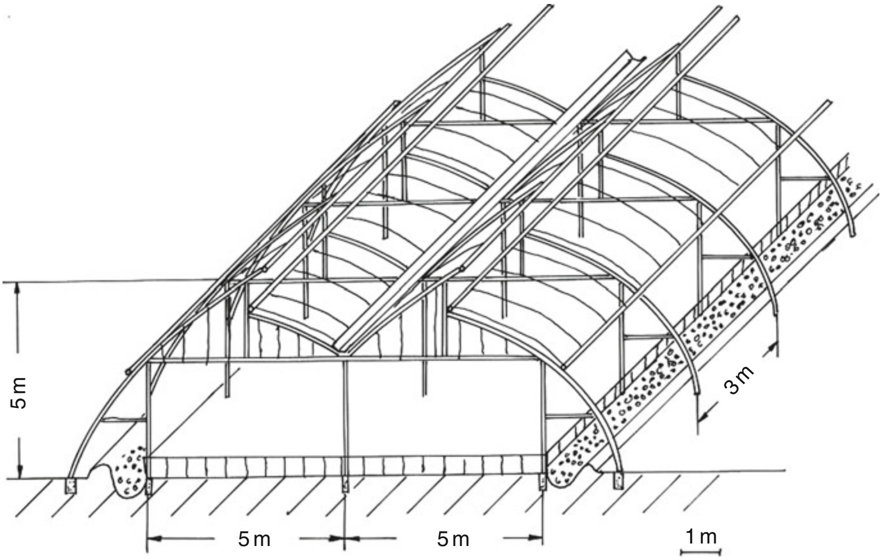



**Fig. 5.40** Very stable steel tube structure from India, with bent roof and side wall tubes

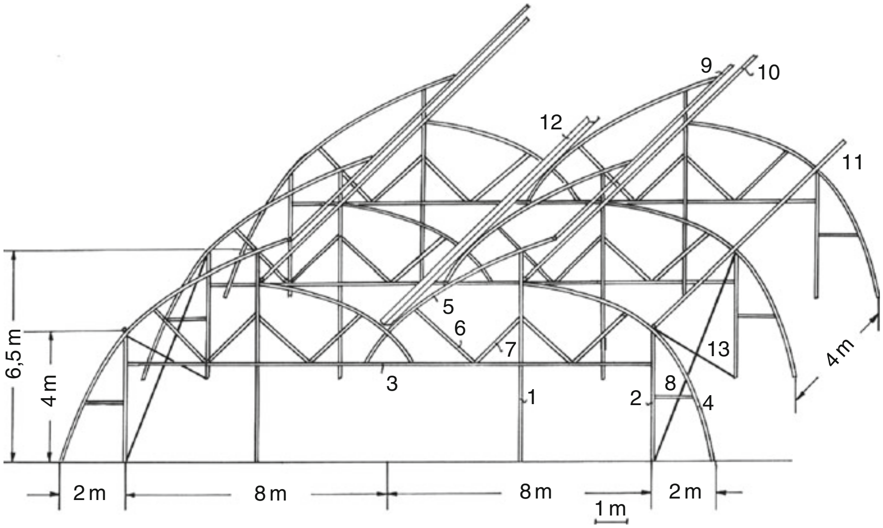



**Fig. 5.41** Double-span steel tube structure from India, which can be equipped with roll-up ventilation at side wall and ridge for tropical highlands also. Remarkable is the position of the main stanchion below the ridge and not below the gutter. The dimensions of the components are given in Table 5.3

**Table 5.2** Shows the dimensions of the components in Fig. 5.34

| Designation | Cross section (mm) | Length (m) |
|---|---|---|
| 1 | 102 × 50 | 2.25 |
| 2 | 102 × 50 | 4.25 |
| 3 | 102 × 50 | 3.25 |
| 4 | 102 × 50 | 3.0 |
| 5 | 50 × 50 | 3.9 |
| 6 | 50 × 50 | 3.8 |
| 7 | 50 × 50 | 3.0 |
| 8 | 50 × 50 | 4.8 |
| 9 | 50 × 50 | |
| 10 | 50 × 50 | |
| 11 | 50 × 50 | |
| 12 | 50 × 50 | |
| 13 | 50 × 50 | |
| 14 | 50 × 50 | |
| 15 | 50 × 50 | |
| 16 | 38 × 38 | |
| 17 | 50 × 70 | 12.0 |
| 18 | 38 × 38 | 0.75 |

**Table 5.3** Dimensions of the components in Fig. 5.41

| Designation | Diameter (inches) | Length (m) |
|---|---|---|
| 1 | 2½″ | 6.5 |
| 2 | 2½″ | 4 |
| 3 | 2″ | 16 |
| 4 | 1½″ | 9 |
| 5 | 1½″ | 7.5 |
| 6 | 1½″ | 2.5 |
| 7 | 1″ | 2 |
| 8 | 1″ | 1.5 |
| 9 | 1¼″ | |
| 10 | 1¼″ | |
| 11 | 1¼″ | |
| 12 | 1 mm metal sheet | |
| 13 | Wind brace | |

## 5.6 Screen and Shade Houses

Shelter structures in subtropical and tropical areas are covered sometimes only by plastic screens, nets or simple natural branches Figs 5.64–5.67. Teitel (2006) reported that insect-proof screenhouses completely covered by screens became popular in recent years in Israel and other Mediterranean countries because of the lower investment compared to other greenhouses.

Screenhouses can be used, for example, for all-year-round production at two different sites, whose harvesting periods are complementary. Vegetable production can be transferred to screenhouses in highlands when the temperatures are too high in coastal areas during summer in subtropical areas (Castilla and Hernandez 2007; Montero 2009) (Fig. 5.64).

The cladding materials of these shelters

- Reduce the impact of heavy rain fall
- Reduce too high global radiation and influence temperature and humidity
- Reduce the influence of heavy wind and hail on the crop
- Reduce the penetration of pest insects and birds

Photoselective nets and screens have been designed to get specific physiological responses, to transform direct light into scattered light, which improves the penetration of light into the plant canopy, and to influence pest control (Shahak et al. 2009) (see Sect. 7.3).

The *disadvantages* of those net or shade houses are:

- The plants are permanently wetted by rain and infested by diseases.
- There is no positive effect on spraying efficiency.
- There is no positive effect of fertilization and water-use efficiency. Fertilizers will be washed out.

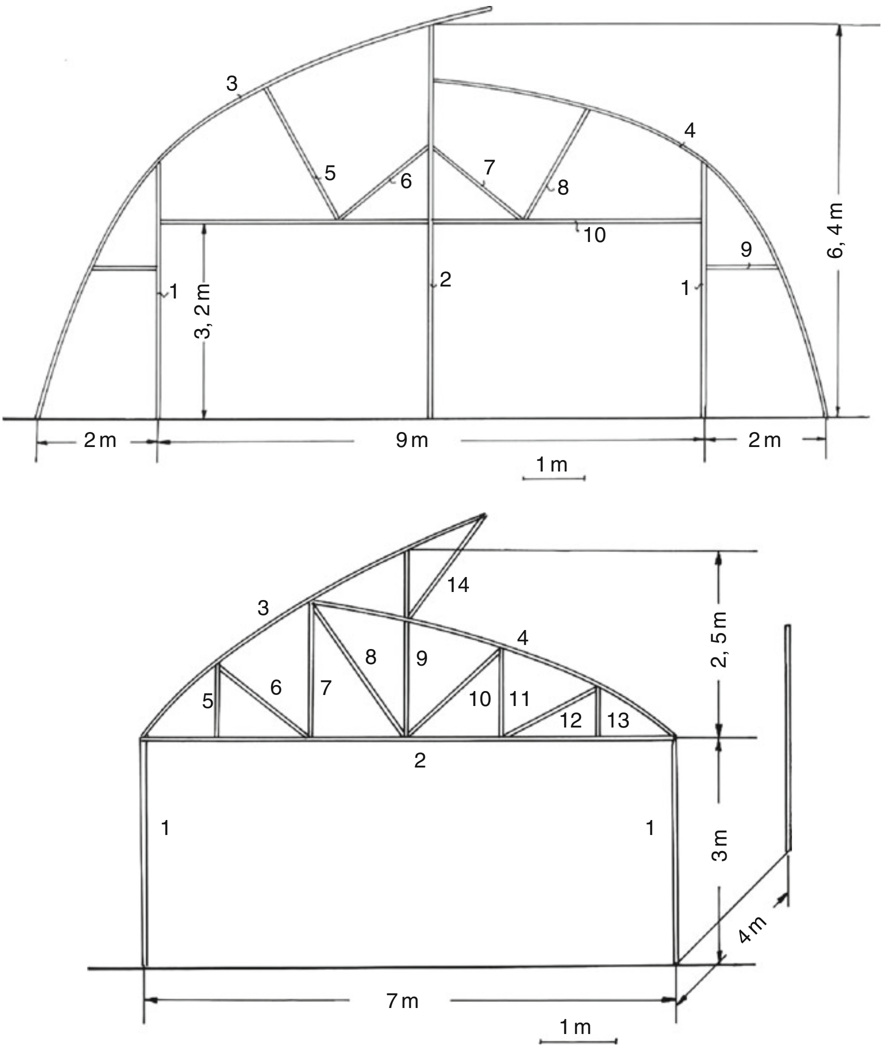



**Fig. 5.42** A comparison of two different trusses made and used in India

Another disadvantage is the decreasing temperature at night in winter. To overcome this problem, many net houses are covered by 50 μm-thick plastic film in winter, with the consequence of reduced light transmittance by two cladding materials.

Screenhouses may be limited to regions with very low rainfall during the cropping season (Figs. 5.65, 5.66).

**Table 5.4** Dimensions of the bent truss tubes in Fig. 5.42

| Designation | Diameter (inches) | Length (m) |
|---|---|---|
| 1 | 2½″ | 4.2 |
| 2 | 2½″ | 6.4 |
| 3 | 1½″ | 10.74 |
| 4 | 1½″ | 9.5 |
| 5 | 1¼″ | 2.5 |
| 6 | 1″ | 2.0 |
| 7 | 1″ | 2.0 |
| 8 | 1½″ | 2.0 |
| 9 | 2″ | 1.25 |
| 10 | 2″ | 9.0 |

**Table 5.5** Dimensions of the welded truss in Fig. 5.42

| Designation | Cross section (mm) | Length (m) |
|---|---|---|
| 1 Tube | 2″ | 3 |
| 2 Angle iron | 35 × 35 × 4 | 7 |
| 3 Angle | 30 × 30 × 3 | 5.5 |
| 4 Angle | 30 × 30 × 3 | 5.25 |
| 5 Angle | 30 × 30 × 3 | 1 |
| 6 Angle | 30 × 30 × 3 | 1.5 |
| 7 Angle | 30 × 30 × 3 | 1.75 |
| 8 Angle | 30 × 30 × 3 | 2 |
| 9 Angle | 35 × 35 × 4 | 2.5 |
| 10 Angle | 30 × 30 × 3 | 1.75 |
| 11 Angle | 30 × 30 × 3 | 1 |
| 12 Angle | 30 × 30 × 3 | 1.5 |
| 13 | 30 × 30 × 3 | 0.5 |
| 14 | 30 × 30 × 3 | 1.75 |

Summarising, one can distinguish three main groups of screens and nets (see Sect. 7.3):

1. Shading materials, black and clear, that reduce solar radiation and wind influence.
2. Coloured screens that filter out colours of the light spectrum.
3. UV-blocking screens that reduce the penetration of UV-radiation.

Romacho et al. (2006) investigated screenhouses covered with clean and alternately green nets, both 6 × 6 threads/cm$^2$ (15 mesh), in the highlands of southern Spain. The transmittance of the screenhouses was about 60% and the temperatures were similar under both nets; slightly higher in the morning and slightly lower in the afternoon compared to outside temperature. The total tomato yield was between 5 and 7.2 kg/m$^2$ in two growing seasons.

Medany et al. (2009) compared sweet pepper crop growth in net-covered tunnel screenhouses and a PE-film-covered tunnel greenhouse in Egypt. The sweet pepper

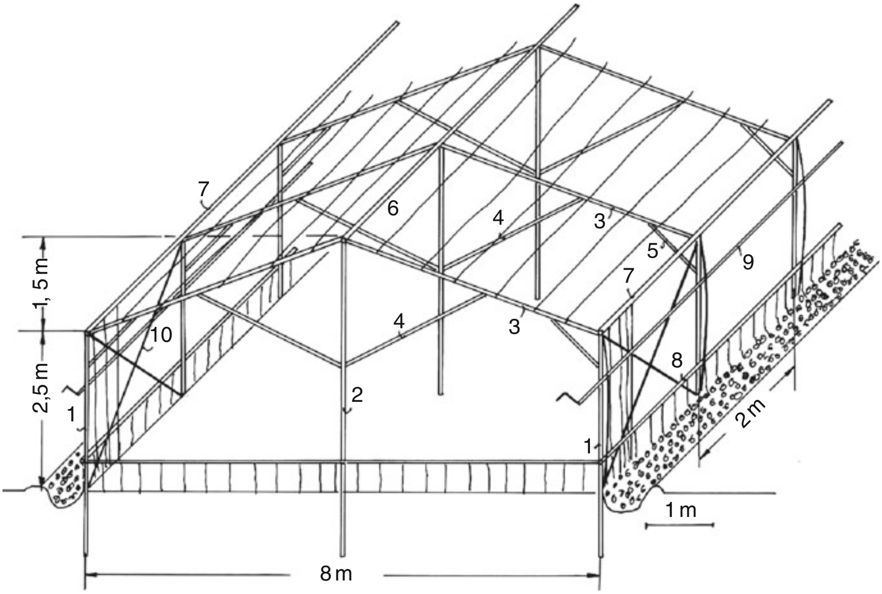



**Fig. 5.43** An example for a simple wooden structure with 8 m span width and roll-up ventilation. The dimensions of the components are listed in Table 5.6

**Fig. 5.44** A well-designed wooden structure in Albania

crop was transplanted in August ,and the cladding materials of the 9 × 40 m tunnels were:

- Black insect-proof screen, 40% shading, and additional 50 μm PE film in winter
- White insect-proof screen, 40% shading; and additional 50 μm PE film in winter
- PE film, 200 μm thick

The temperature difference inside to outside was 1–3°C in the screenhouses and 3–5°C in the plastic-film greenhouse. Early yield was highest in the black

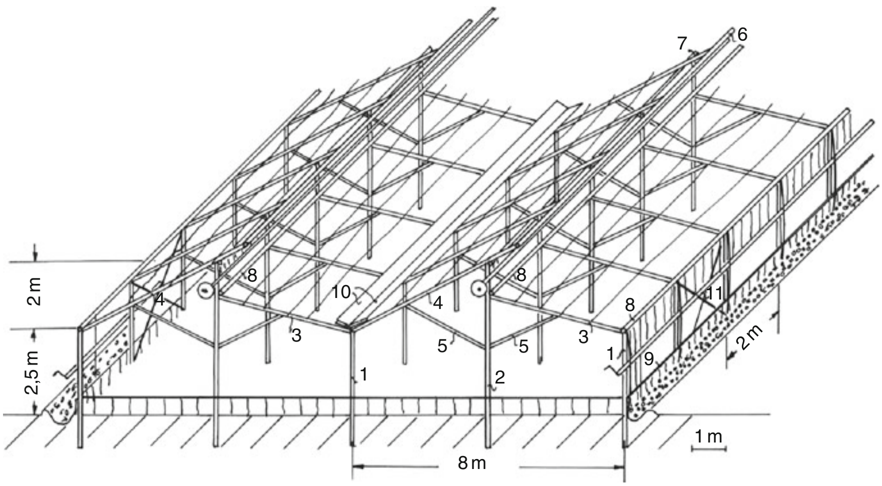



**Fig. 5.45** Wooden structure with roll-up side wall ventilation and vertical ridge ventilation. Dimensions of the structure n are listed in Table 5.7

screenhouse, but total yield was the lowest. Total yield was highest in the white screen tunnel. The white screen cover plus 50 μm plastic film in winter was the best choice for sweet pepper under the climate conditions in Egypt.

Experiments were carried out in a commercial flat-top screenhouse, 3.2 m high, 60 by 110 m floor area, located in Israel, 32° 16′N. The cladding material was a 50-mesh screen, 50 threads per inch and 0.24 mm thread diameter (Tanny et al. 2003; Möller et al. 2003). The air exchange in the middle of the screenhouses could be expressed by the regression curve

$$N = 3.21 \times v_w + 12.75(1/h)$$

and the theoretical air exchange for a pepper crop in the open field with wind speeds between 1.5 and 3.5 m/s

$$N = 23.82 \times v_w(1/h)$$

where $N$ = air exchange number and $v_w$ = wind speed (m/s).

The reduction of ventilation rate was 51–71%. The temperature inside near the screen was similar to the outside temperature, and the temperature gradient from the upper level to the lower crop level was up to 5°C in the middle of the day (Tanny et al. 2003).Other measurements showed a relatively constant temperature gradient over the height (Möller et al. 2003).The mean temperature difference inside to outside was between −2°C and +2°C, and did not exceed +2.5°C (Möller et al.

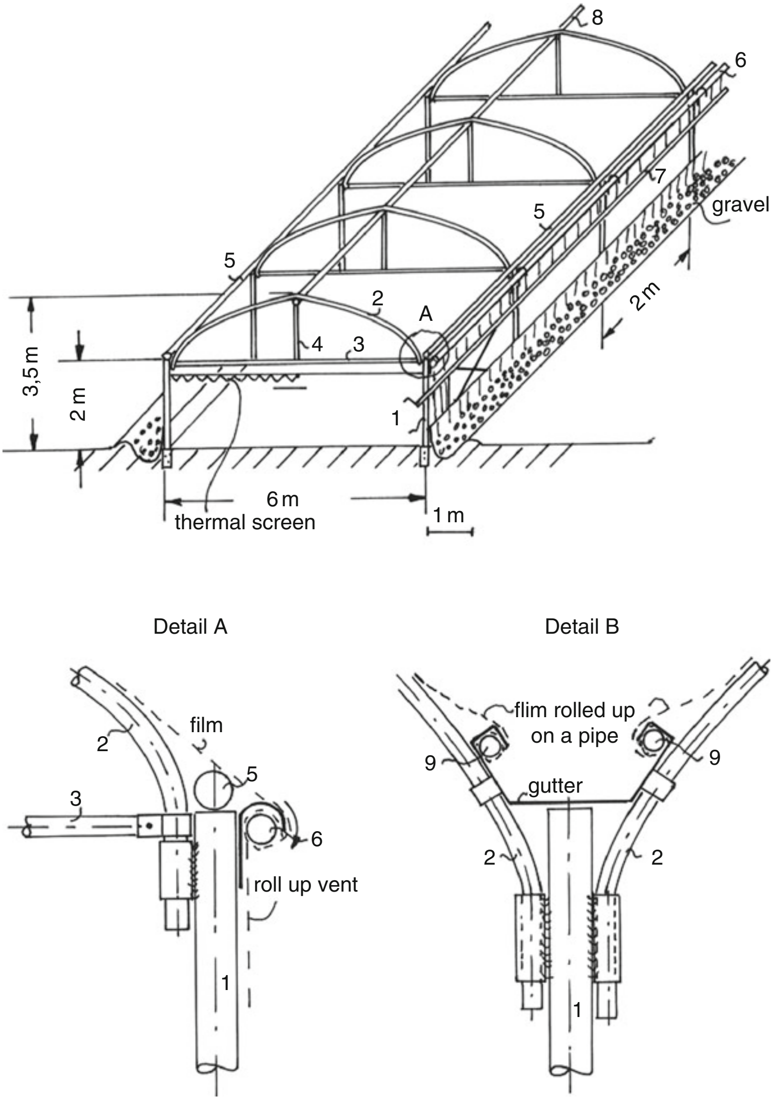



**Fig. 5.46** Pointed-arched steel tube structure with a moveable thermal screen and gutter at side wall on the ground level. The plastic film of roof covering and roll-up ventilation at side wall are fixed and stretched by one steel tube (detail *A*). The plastic film is rolled up on a tube in a profile of the gutter (detail *B*). The dimensions of the components are listed in Table 5.8

2003). The outside wind speed was reduced by 75–95% above the pepper crop (Fig. 5.67).

The height of the screenhouse has an influence on the microclimate. Two screenhouses of 2 m and 4 m height respectively were investigated, covered with a screen of 60% shading and 3 × 2 mm hole size (Tanny et al. 2003):

**Fig. 5.47** Multi-span greenhouse in Morocco. The ventilation opening may be not sufficient

**Fig. 5.48** Multi-span structure with roll-up ventilation in Cyprus

- The net radiation was almost identical.
- The air temperature near the plants and the leaf temperature were higher in the lower screenhouse. The average daily air temperature difference between the two screenhouses was 1.5°C, and maximum difference at noon was 2.7°C.
- The vertical temperature gradient was about three times larger in the lower screenhouse.
- The absolute humidity was closer to the outside humidity in the higher screenhouse.
- The climate for workers is more comfortable in higher screenhouses.

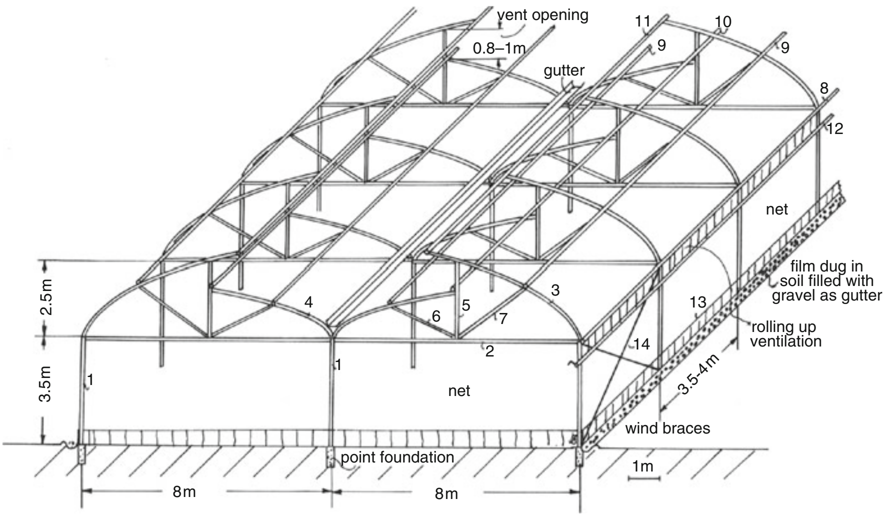



**Fig. 5.49** Steel tube structure with side wall and ridge vents that are open in opposing directions in both spans for better ventilation efficiency. The roll-up ventilation at the ridge is not drawn in for better overall view. The components are connected by clamps. The dimensions are listed in Table 5.9

Higher screenhouses up to 5 m are more advantageous than lower heights, as 3.5 m, with regard to temperatures and humidity (Montero 2009).

Most of the protected cultivation on the Canary Islands is under screenhouses, but they do not protect the crops against rain and very low-humidity conditions. Farmers are therefore thinking about changing to plastic film greenhouses (Santos et al. 2006). A Parral-type screenhouse, covered by a screen with 10 × 14 threads/cm$^2$, 35 mesh, 36% porosity, has a mean transmittance of 70% for global radiation when the screen is clean. The transmittance decreases over time to lower than 60% by dust accumulation. Rainfall cleans the screen again to higher transmittance.

## 5.7 Specific Greenhouses

### *5.7.1 Parral Type, Almeria*

One of the most widespread greenhouse types in the area of Almeria, South Spain, is the Parral type with flat roof or with low roof slope built by local workmen (Fig. 5.68). Wooden or steel poles, vertical in the middle and sloped at the side wall, are connected crosswise by wires at the top, and two wire grids are tightened over the construction. The plastic film is placed in between the grids. About 33% of the area is still covered by these flat-roof types (Castilla and Hernandez 2005).

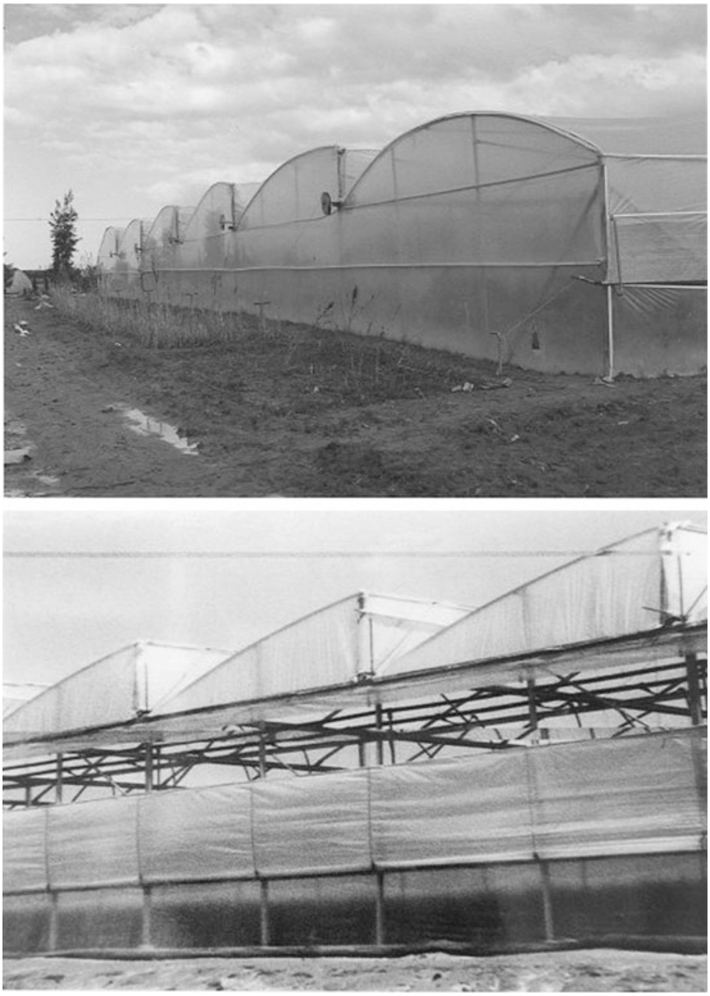


**Fig. 5.50** Shed roof with roll-up ventilation at vertical ridge in Israel and Tunisia

The Parral-type greenhouse has some disadvantages (Perez-Parra et al. 2004):

- The drop condensation at the flat roof reduces light transmittance and thus yield and quality (Fig. 5.69).
- Drops falling off the roof wet the crop and encourage diseases. Some growers stretch extra plastic film below the roof to prevent drop fall (Fig. 5.70).
- Ventilation efficiency by side walls only is not sufficient.
- The Almeria area has relatively low rainfall. Therefore, flat roofs may be sufficient, but for regions with higher amounts of rainfall such as Antalya, South Turkey, the flat roof is not suitable because water pockets form on the flat plastic film and may destroy the film, Fig. 5.71.

**Fig. 5.51** Greenhouse structure with open ridge and roll-up vent at side wall in India. For tropical highlands, roll-up vents at ridge are preferable

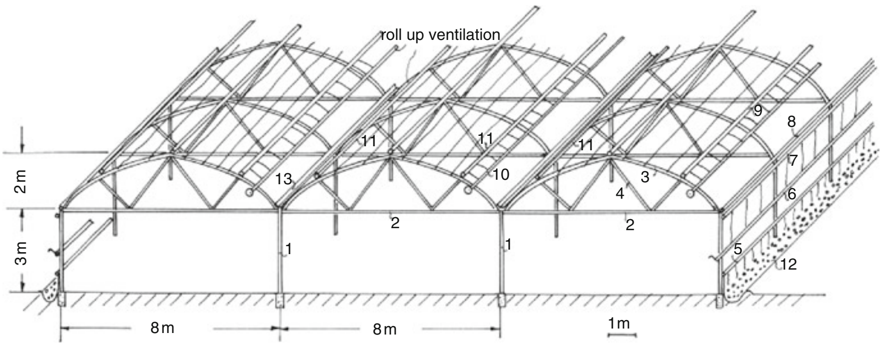



**Fig. 5.52** Multi-span structure with roll-up ventilation at roof and side wall (see Sect. 5.2). Dimensions are listed in Table 5.10

Asymmetrical or symmetrical saddle-roof constructions with roof vents were improvements to the Parral type, done in particular for ventilation efficiency (see Chap. 9).

The yield of cucumbers was 25–50% higher in an asymmetrical east–west-oriented and unheated greenhouse with a roof slope of 45° to the South and 27° to the north, in comparison to a type with 11°/24° respectively (Castilla et al. 2001).

**Fig. 5.53** Greenhouse structures with different ventilation openings at roof and ridge in Israel. The gutter height is 4 m minimum

**Fig. 5.54** Greenhouse with flap ventilation and high side wall in Turkey. The side wall is double-inflated

The average greenhouse structure costs including plastic film for 1 ha in the South of Spain were (Castilla et al. 2005) (Figs. 5.72, 5.73)

| | |
|---|---|
| Low roof slope structure | 7.8 €/$m^2$ |
| High roof slope structure multi-span | 10.2 €/$m^2$ |
| Arched shape multi-span | 15.6 €/$m^2$ |

**Fig. 5.55** Greenhouse structure with alternate roof openings. The roof opening is linked to the gutter, and opens at the ridge. The height of the gutter is more than 4 m

### *5.7.2 Greenhouses for Banana*

Some Mediterranean countries grow banana in greenhouses, for example Tunisia and Morocco. These banana greenhouses have an extra height of up to 8 m. The greenhouses protect the bananas from low temperatures, and provide them a suitable climate. The constructions have to be secured against wind forces by several extra braces (Fig. 5.74).

### *5.7.3 Greenhouses for Terraces*

Vegetables and fruits are cultivated on small terraces in some tropical countries, for example the Seychelles (Fig. 5.75). The terraces have a width of 2–4 m. Growers used to build very simple terrace shelters to protect the crop from too heavy rainfall (Fig. 5.76), but many of them were soon destroyed by heavy storms. Therefore, shelter structures for terraces have to be adapted to the individual form of the terraces and designed to be wind-resistant. Thus, more wind-resistant terrace greenhouses have been designed and introduced into practice (Fig. 5.77–5.80) (Von Zabeltitz 1996a, b). At first, the plastic film was nailed onto the structure, which is not to be recommended. New structures were designed, built using timber profiles (Fig. 5.78), where the plastic film can be fastened and stretched by rolling it up on steel tubes. In this way, the plastic film can be stretched at any time when it is stretched by temperature, and when it starts to flutter due to wind. The structure has gutters to collect and drain off rainwater (Figs. 5.79).

**Fig. 5.56** Greenhouse in China. A round-arched structure is leaned against a north wall, and will be covered by straw mats at night

**Table 5.6** Dimensions (mm) of wooden structure in Fig. 5.43

| Component No. | Dimension (mm) |
|---|---|
| 1 | 100 Ø or 76 × 127 |
| 2 | 100 Ø or 76 × 127 |
| 3 | 50 × 100 |
| 4 | 50 × 100 |
| 5 | 25 × 50 |
| 6 | 50 × 50 |
| 7 | 50 × 50 |
| 8 | 25 × 50 or tube 25 Ø |
| 9 | Steel tube 25 Ø |
| 10 | Wire for windbrace |

**Table 5.7** Dimensions of the wooden structure in Fig. 5.45

| Component No. | Dimension (mm) |
|---|---|
| 1 | 100 Ø or 76 × 127 |
| 2 | 100 Ø or 76 × 127 |
| 3 | 50 × 100 |
| 4 | 50 × 100 |
| 5 | 50 × 100 |
| 6 | 50 × 50 |
| 7 | 50 × 50 |
| 8 | 50 × 50 |
| 9 | 25 × 50 |
| 10 | Gutter 25 × 250 |
| 11 | Tube 25 Ø |

**Table 5.8** Dimensions of the steel tube design in Fig. 5.46

| Component No. | Dimension (mm) |
|---|---|
| 1 | 50 |
| 2 | 40 |
| 3 | 40 |
| 4 | 25 |
| 5 | 30 |
| 6 | 25 |
| 7 | 25 |
| 8 | 30 |
| 9 | 25 |
| 10 | Gutter |

## *5.7.4 Tent-type Construction*

A simple plastic-film greenhouse structure suitable for different climates has been designed in the Institute for Horticultural Engineering Hannover (Von Zabeltitz 1985, 1990a) (Fig. 5.81, 5.82). It consists of two parts: the load bearing base

**Table 5.9** Dimensions of the steel tube structure in Fig. 5.49

| Component No. | Dimension (mm) |
|---|---|
| 1 | 60 |
| 2 | 50 |
| 3 | 40 |
| 4 | 40 |
| 5 | 50 |
| 6 | 30 |
| 7 | 30 |
| 8 | 40 |
| 9 | 40 |
| 10 | 40 |
| 11 | 40 |
| 12 | 20 |
| 13 | 20 |
| 14 | Wire for windbrace |

**Table 5.10** Dimensions of the construction in Fig. 5.52

| Component No. | Dimension (mm Ø) |
|---|---|
| 1 | 60 |
| 2 | 50 |
| 3 | 50 |
| 4 | 30 |
| 5 | 25 |
| 6 | 25 |
| 7 | 30 |
| 8 | 50 |
| 9 | 40 |
| 10 | 25–30 |
| 11 | 40 |
| 12 | Gutter |
| 13 | 1 mm metal sheet |

structure and the roof structure. The base structure is a guy-wire construction similar to a tent, with inclined wire ropes or steel rods (*a*) connecting the gutter or upper end of the stanchions respectively to the foundation. Within the spans, the stanchions are connected crosswise at the upper ends by steel rods or wires (*b*). Longitudinally, the stanchions are connected by gutters. The stanchions are loaded only by pressure forces, the other components by tension forces. Only small foundations are necessary below the inside stanchions, while deeper foundations are positioned below the inclined steel rods (*a*). Assembly is simplified, and material costs are reduced.

Advantages:

- Efficient stability with reduced construction components
- Improved light transmittance
- Smaller foundations inside

**Fig. 5.57** A greenhouse structure for desert regions in Kuwait, covered with rigid plastic sheets and equipped with fan and pad cooling

The greenhouse construction stood for 15 years and was resistant against wind and snow forces all the time.

The roof structure in Fig. 5.81 consists of plastic jacketed spring steel rods with a diameter of 20 mm covered with double inflated plastic film. The structure is very resistant to wind, storm and a snow load of 35 kg/m$^2$. With higher snow loads, the spring steel rods bent, but the structure was not destroyed. After removing the snow, the spring steel jumped to the original form.

Force measurements were carried out on the structure. Only pressure forces were measured on the stanchions. Pressure forces of 90–110 dN (deka Newton) were

**Fig. 5.58** A round-arched structure covered with plastic film and permanent shading net, ventilated and cooled by fan and pad system

**Fig. 5.59** Round-arched tunnels in the desert of Tunisia, with hedges and plastic fence as windbreak

measured at wind speeds of 3–6 m/s at the stanchions under the gutter. Even at high wind speeds from various directions, no tensile forces could be measured on the stanchions. Tensile forces of 330–480 dN were measured on the inclined rods (*a*) at both sides, at wind speeds of 5–6 m/s. The tensile forces on the horizontal rods (*b*) were 220–250 dN. Even in a gale, there was no damage to the construction. Different roof structures can be designed Fig. 5.83.

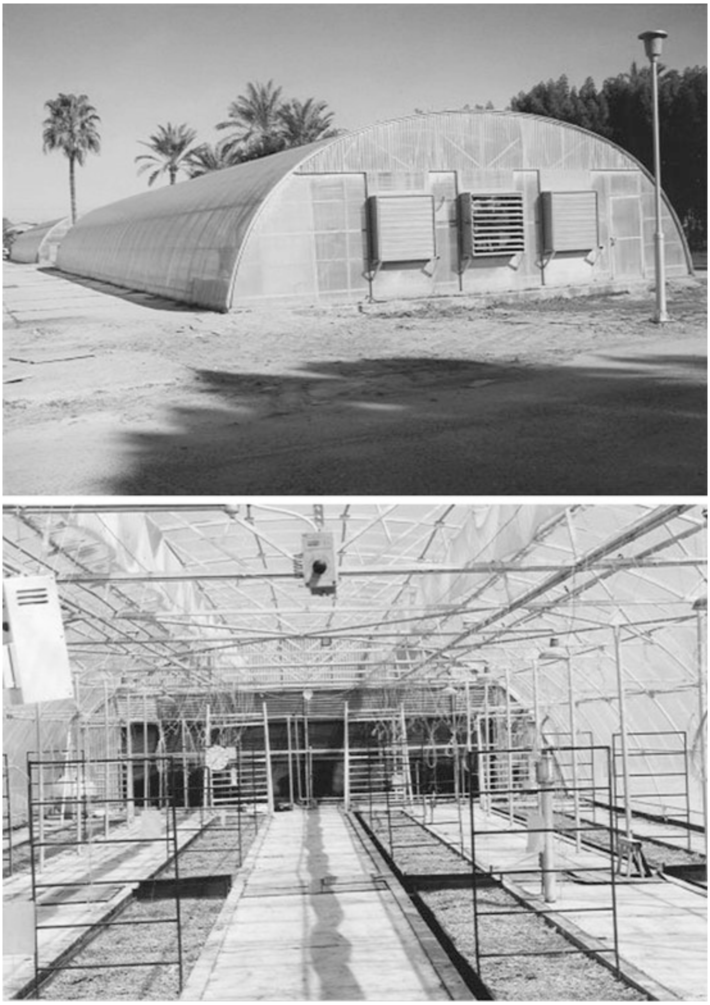


**Fig. 5.60** Round-arched tunnel with fan and pad cooling at gable ends in Kuwait

The structure has a cladding of double inflated plastic film for stabilizing and energy-saving purposes. Even the roll-up vents on the side wall can be inflated. In the closed position, the double film is inflated and therefore very tight, without leaks at the edges. When the film is rolled up for ventilation, the excess air must have the possibility to escape during rolling up. There is a very simple flap valve with a counterweight installed, which keeps the valve closed against the air pressure and opens when the pressure increases during the rolling up of the vent, Fig. 5.84. This self-made valve has worked safely for years (Figs. 5.85). The roll up ventilation on both sides can be operated by out driving motor, Fig. 5.86. A commercial structure has been designed, Fig 5.87.

**Fig. 5.61** Round-arched tunnel with fan and pad cooling at side wall in Kuwait

## 5.8 Life Cycle Assessment, LCA

"Life Cycle Assessment is a process to evaluate the environmental burdens associated to a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment to affect environmental improvements." (Society of Environmental Toxicology and Chemistry, SETAG 1993).

Russo et al. (2005) defined the LCA as an "instrument which provides a quantitative estimate of all flows of matter and energy related to the realization of a product, providing an evaluation of the environmental compatibility and end result of each productive choice".

The LCA considers the entire life cycle of a product from resource extraction to waste disposal (Anton et al. 2003). The LCA method can be applied to horticultural production and to greenhouse structures and equipment, as well as to comparison of crop production in different countries.

The aim of the LCA is to compile the entire knowledge about environmental impact of products and processes during the life cycle, and to give the possibility to compare products (greenhouse construction) or even crop production in different countries (Van der Velden 2004; Schüsseler and von Zabeltitz 2004).

The procedures of the LCA are described in different standards (ISO 14040, ISO 14042, DIN EN ISO 14040, DIN EN ISO 14043). A LCA study can be divided into four steps (Schüsseler and von Zabeltitz 2004, Anton and Montero 2003):

1. The goal and scope definition describes the system under investigation (greenhouse construction), its function and boundaries.

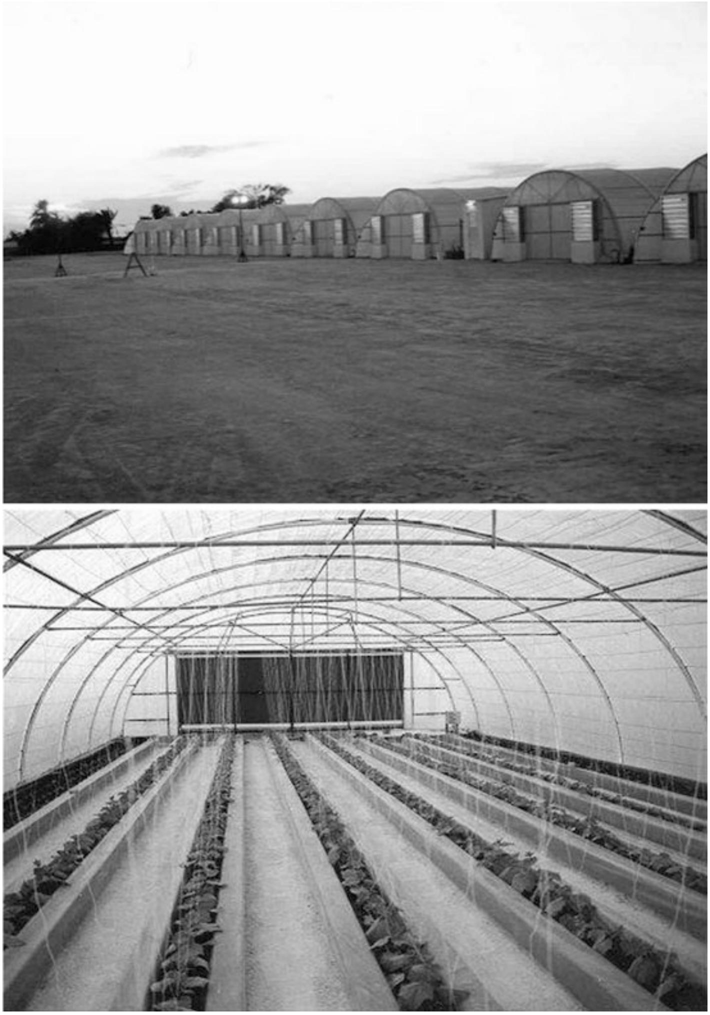


**Fig. 5.62** Round-arched tunnel greenhouses with fan and pad cooling and hydroponics in the desert of Quatar

2. The inventory analysis compiles the resource consumption associated with the system. The potential environmental impact of the various emissions and resource consumption is not considered in this phase.
3. The life cycle impact assessment evaluates the inventory data with regard to their potential to harm the natural ecosystem, human health and resources. Special impact categories and indicators are defined, for example energy consumption, climate change by $CO_2$ emission, toxicity, water consumption, soil pollution, and others.

**Fig. 5.63** Shed roof structure covered with corrugated polyester sheets. Those sheets are not recommendable anymore, because the light transmittance decreases within a short time and the sheets are relatively expensive.

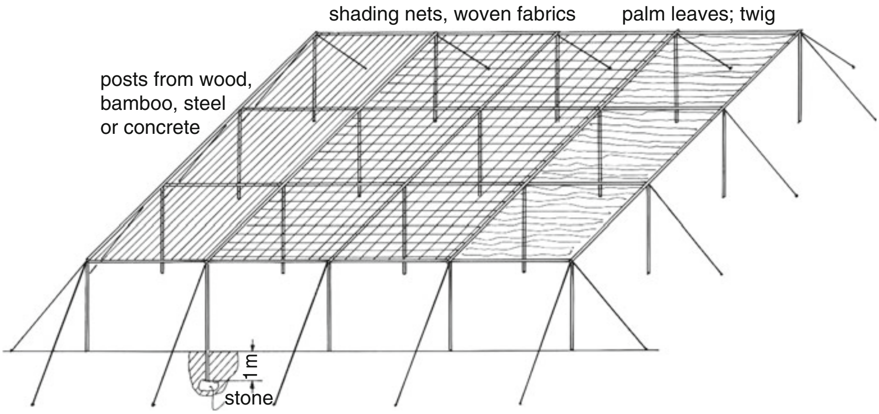



**Fig. 5.64** Design of net and shade house

**Fig. 5.65** Shade house in Southeast Asia

**Fig. 5.66** Tunnel structures covered with nets to protect the crop from birds and insects

**Fig. 5.67** Net houses in Thailand and India

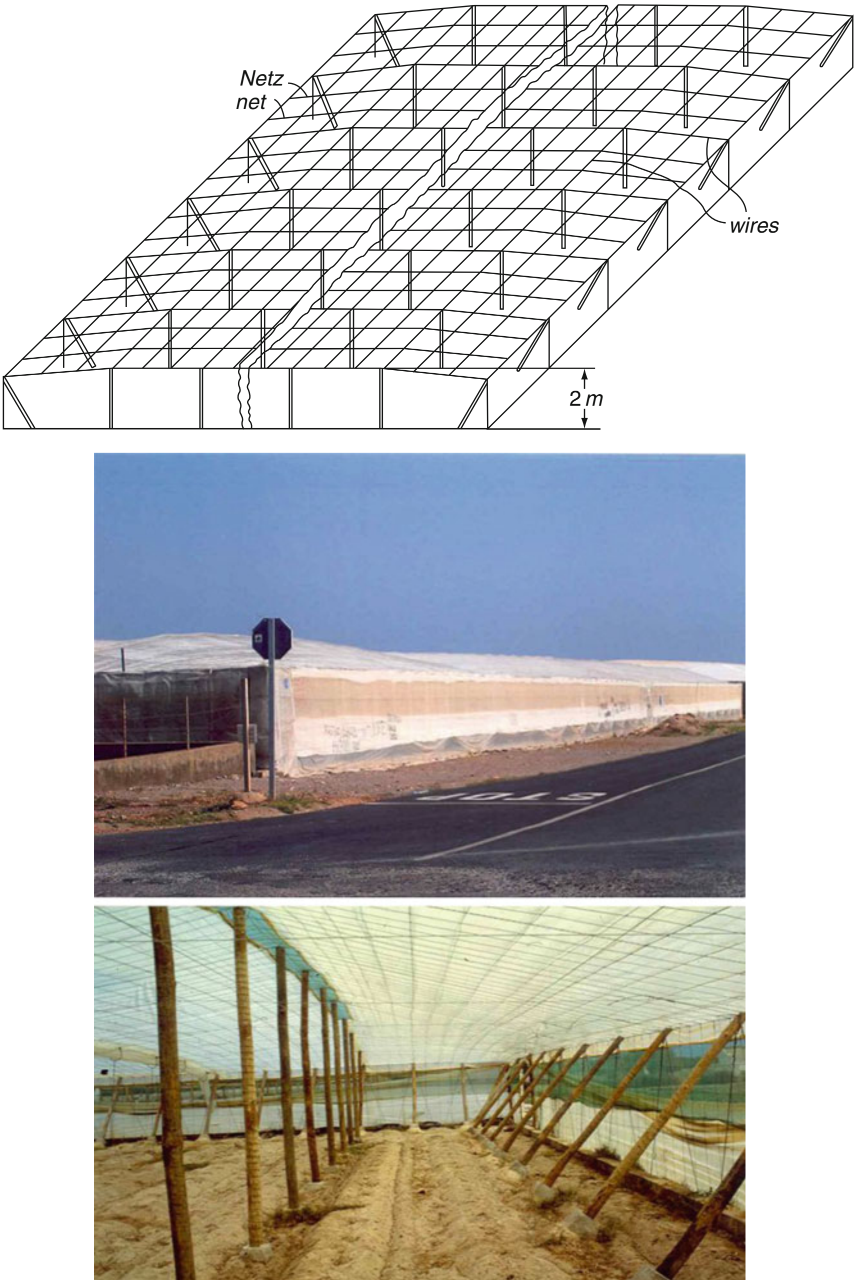



**Fig. 5.68** Parral-type greenhouse in Almeria with flat roof

**Fig. 5.69** Drop condensation on flat roofs of Parral type

4. In the interpretation phase, the results of the inventory and impact assessment are discussed. Conclusions will be drawn to define options for the improvement of environmental performance of the system under investigation.

One important factor for crop production in greenhouses should be "sustainable development that meets the needs of the current generation without undermining the ability for future generations to meet their own needs" (De Pascale and Maggio 2005).

Sustainable production can be judged by the following indicators (De Pascale and Maggio 2005):

- The use of non-renewable resources
- The use of renewable resources
- The level of pollution

Horticultural production produces performance and causes environmental burdens (Fig. 5.88) (von Zabeltitz 1997). Sustainable production means valence of performance > valence of environmental burdens.

The question is: how can we assess the environmental burden?

Greenhouse crop production has a smaller environmental impact than open-field production in many cases.

Munoz et al. (2008) compared the environmental impacts of tomato production in a greenhouse and open field in a Mediterranean region (41°, 31′N) near Barcelona, Spain. The greenhouse was a 5,000 $m^2$, six-span steel frame structure, 4 m gutter height, 5.5 m ridge height, with six roof and two side vents. No heating was in operation.

**Fig. 5.70** Extra plastic film stretched below the roof to prevent wetting of plants by drop fall. This method takes a lot of necessary light transmittance

The phases of greenhouse production, transportation of materials, installation and waste management were considered as well as irrigation, fertigation and water pumping. All field operations by tractors and agricultural machinery, the energy for raw materials, repair and maintenance, as well as fuel consumption and production of fertilizers, were considered for open-field production.

The tomato yields were:

8.6 kg/m$^2$ in the open field
16.5 kg/m$^2$ in the unheated greenhouse

**Fig. 5.71** Water pockets in the plastic film of flat roof

Most of the impact categories related to 1 kg of tomato production were lower in greenhouse production. A comparison brought the following results for tomatoes (Montero 2009; Montero et al. 2008a; Munoz et al. 2008):

| Impact category | Greenhouse | Open field |
|---|---|---|
| Global warming (kg $CO_2$/kg) | 7.44 E−02 | 5.01 E−02 |
| Energy consumption (MJ/kg) | 0.94 | 1.19 |
| Water consumption (L/kg) | 24.4 | 42.84 |

The production of the greenhouse structure (steel and concrete) had the greatest influence in the global warming category, measured in kg $CO_2$ equivalent per kg tomato. Forced ventilation and heating increase the environmental impact considerably.

In addition to higher productivity in comparison to open-field production, and other advantages such as water-use efficiency, there are noticeable negative environmental impacts through greenhouse crop production, for example:

- Negative landscape impact in regions with high density of greenhouse crop production like Almeria, Spain, Ragusa, Italy, and Antalya, Turkey (De Pascale and Maggio 2005).
- Waste of plastics
- Energy consumption

The plastic consumption for protected crops in Italy is about 80,000 tons per year, and the estimated consumption for plastic covering is 2.2-3 tons per ha and year in the Campania region (De Pascale and Maggio 2005). The consumption for plastic film for recovering in the Almeria area is about 1.1 tons per ha and year. In Germany, the plastic film consumption for recovering greenhouses is about

**Fig. 5.72** The Parral-type constructions were improved to asymmetrical saddle-roof types with different roof slopes

1.5–1.8 tons per ha and year, and altogether 600–720 tons per year for 400 ha of plastic film greenhouses.

Possibilities for reducing the waste of plastic are recycling and burning, and the use of long-life plastic film. About 30% of the plastic used in greenhouse industry is recycled (La Malfa and Leonardi 2001). The possible use of low-grade recycled plastic is limited. In Germany, most of the plastic will be burned for energy consumption. Burning for energy consumption is recommendable as second-hand use for the raw material oil.

**Fig. 5.73** Industrial manufactured high-arched greenhouses are used in particular for flowers

The consumption of chemicals for pest management is normally higher in warmer climates than in temperate climates. An estimated amount of 47 kg/ha of active ingredients is used for the most intensive Italian greenhouses versus 31 kg/ha in the Netherlands (Stanghellini et al. 2003). A remarkable reduction of pesticides can be achieved by IPP (Integrated Production and Protection) management.

A comparison of the environmental input of greenhouse crop production in Netherlands and Spain has been evaluated (Van der Velden and Janse 2004). The energy consumption and crop protection for various vegetable crops was examined for the Spanish regions Almeria and Murcia versus the Netherlands. The physical production rate is significantly lower in Spain than in the Netherlands:

| | Physical production (kg/m$^2$) | | |
|---|---|---|---|
| | Tomato | Sweet pepper | Cucumber |
| Almeria | 9 | 6 | 9 |
| Murcia | 8 | 8 | |
| Netherlands | 50 | 26 | 70 |

This is caused by a shorter cultivation period, limited light availability in winter, low temperatures in unheated greenhouses, unsuitable air humidity and limited use of greenhouse technology.

The primary fuel consumption per kg of vegetable in the Netherlands is estimated to be higher by 13 times for tomatoes, 14–17 times for sweet pepper and nine times for cucumber than in Spain.

Not only energy and consumption of chemicals, but even the transport has to be considered. Figure 5.89 shows the total consumption of energy (MJ/kg tomato) for production and transport of tomatoes from different countries to Frankfurt in Germany, as well as the consumption of active ingredients (g/kg) (Verhaegh 1996).

**Fig. 5.74** Greenhouses for bananas

**Fig. 5.75** Vegetables and fruits cultivated on terraces in the Seychelles

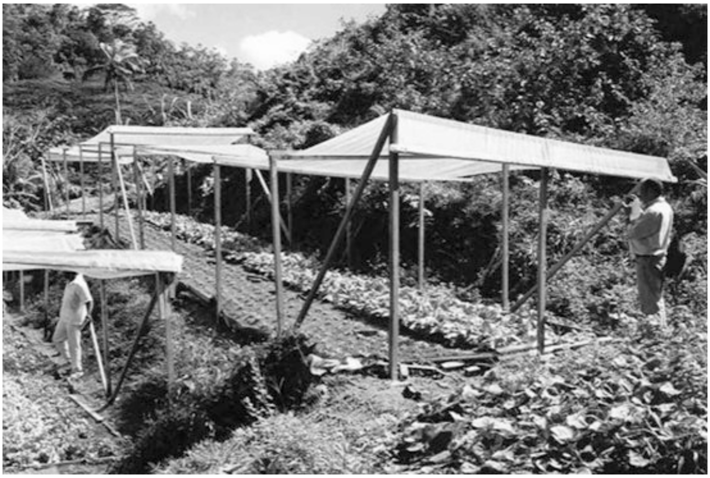


**Fig. 5.76** Simple but not wind-resistant terrace shelters in the Seychelles

**Fig. 5.77** Wooden structure for terrace shelter with nailed-on plastic film in the Seychelles

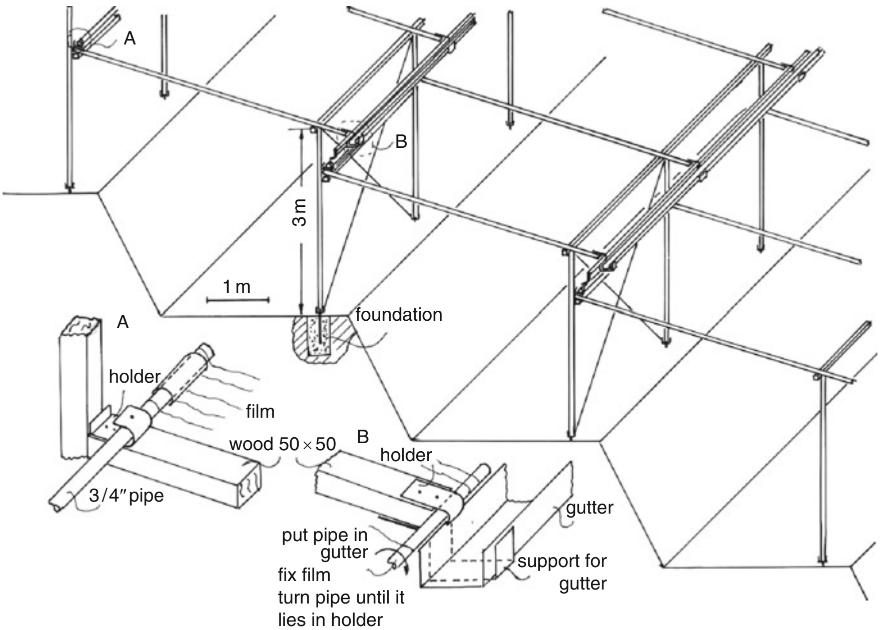



**Fig. 5.78** Wooden terrace greenhouse structure with gutter and devices for fastening and stretching the plastic film

The energy consumption in the Netherlands is highest because of the need for heating in winter; energy for transport is only remarkable for flight transport from Israel. The total energy consumption for tomatoes from southern countries with transport by truck is relatively low. The consumption of active ingredients for pest control is much higher in southern countries than in temperate climates.

The total energy consumption per stem of roses from the Netherlands is comparable to that from southern countries with transport by air freight. The consumption of active ingredients is about 11 times higher in the Morocco than in the Netherlands (Fig. 5.90).

One can make some suggestions how to improve crop production in southern countries, for example to use a little bit more heating to reduce the chemical consumption for pest control.

The environmental compatibility of plastic-film greenhouse structures is higher than for glass houses. This can be judged by the LCA method.

Different glass and plastic-film greenhouses have been investigated by a mass and energy balance (simplified LCA) (von Zabeltitz et al. 1992, Schüsseler and von Zabeltitz 2004).The greenhouses evaluated are described in Fig. 5.91.

The mass and energy balance was calculated uniformly for 2,000 $m^2$.

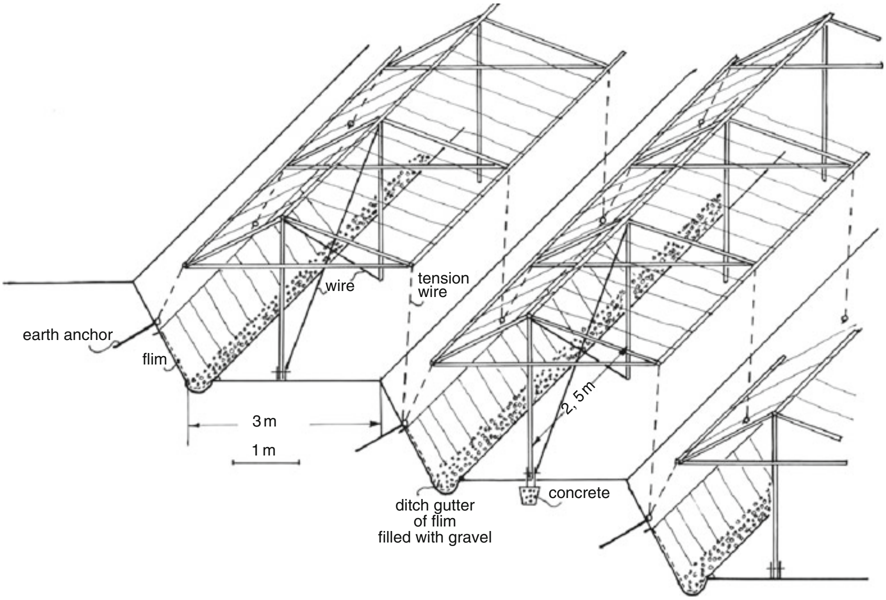



**Fig. 5.79** Umbrella-type for terrace shelter structures, fastened by tension wires and earth anchor. The rainwater can be collected by a plastic film gutter dug into the soil. The plastic film is stretched over the structure and fastened at the edges by self-made clips from PVC water tubes cut open in longitudinal direction

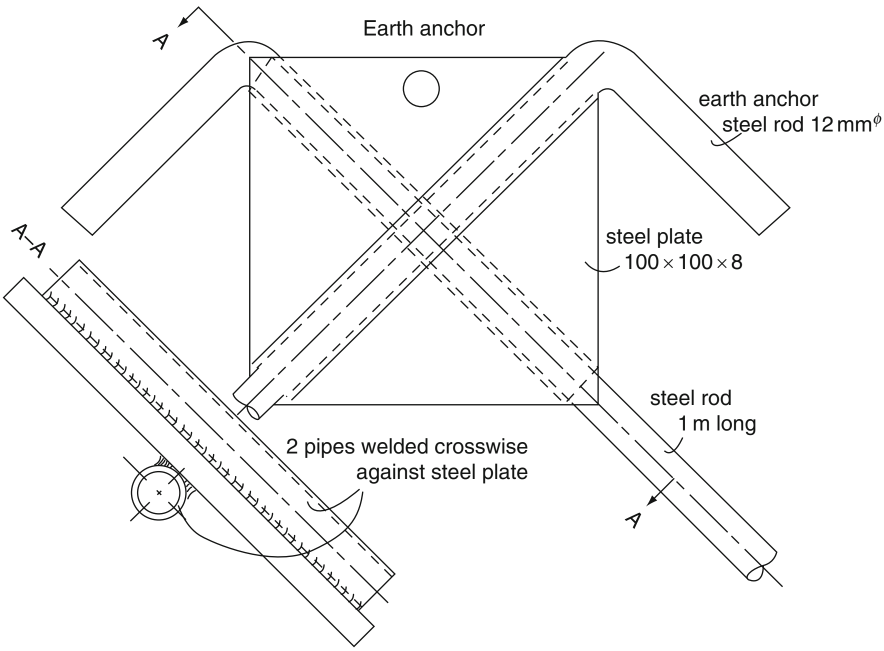



**Fig. 5.80** Some self-made earth anchors for fastening the tension wires. Commercial earth anchors may be expensive or not available. Those earth anchors can withstand relatively high wind forces

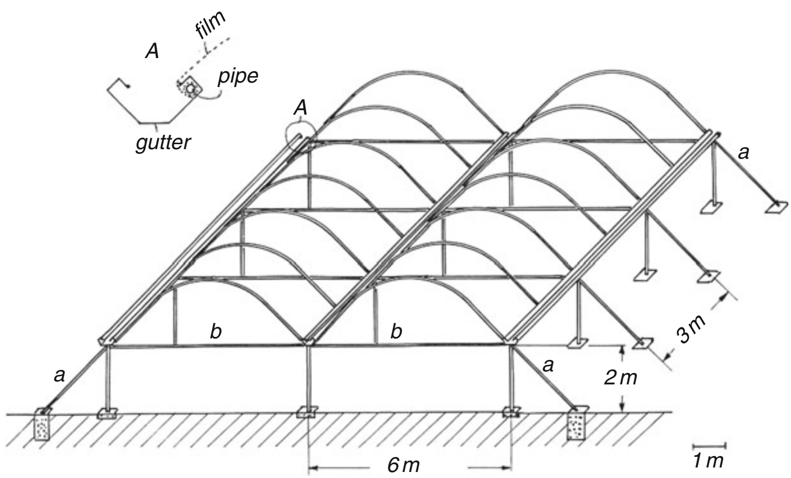



**Fig. 5.81** Tent-type structure, Hannover

**Fig. 5.82** The plastic-film greenhouse, Hannover

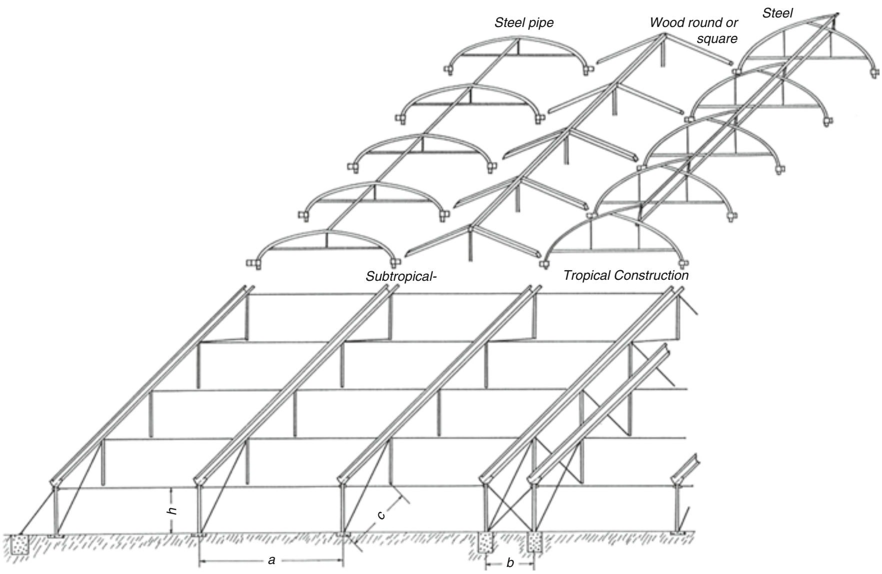



**Fig. 5.83** The independent roof structure can be designed in various forms with different profiles and can be fixed to be wind-resistant to the gutter or the stanchions respectively, for example for subtropical or tropical regions

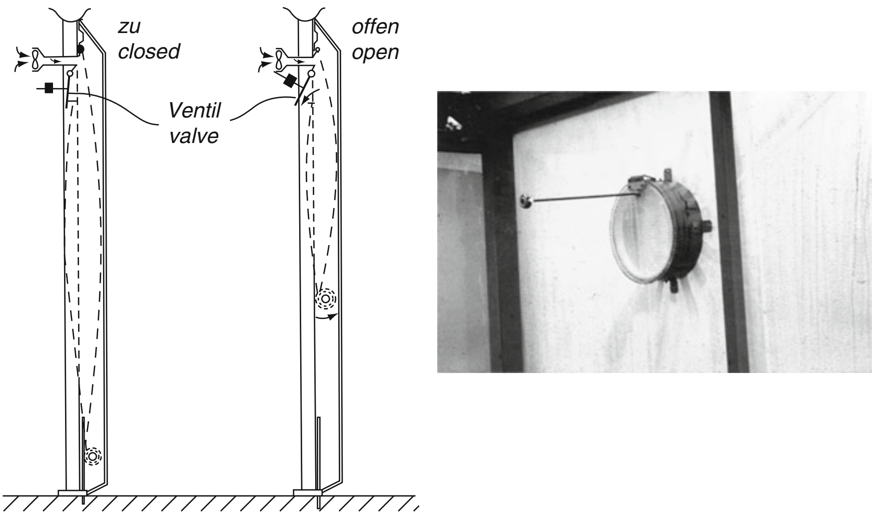



**Fig. 5.84** Roll-up ventilation with double-inflated plastic film

**Fig. 5.85** Meanwhile, commercial valves for the double-inflated film are available

A: Wide span glass greenhouse, steel-aluminium construction.
Width: Five spans of 9.67 m each; Length: 42.9 m; Floor area: 2,075 $m^2$.
B: Venlo type glass greenhouse, steel-aluminium construction.
Width: Five spans of 9.6 m each; Length: 40 m; Floor area: 1,920 $m^2$.
C: Plastic film greenhouse I, single film, steel aluminium construction.
Width: Four spans of 8.7 m each; Length: 56 m; Floor area: 1,949 $m^2$.
D: Plastic film greenhouse II, air cup film, steel construction.
Width: Two spans of 10 m each; Length: 100 m: Floor area: 2,000 $m^2$.
E: Plastic-film greenhouse III, air inflated double film and single film, steel construction.
Width: Five spans of 10 m each; Length: 40 m; Floor area: 2,000 $m^2$.

### *5.8.1 Results*

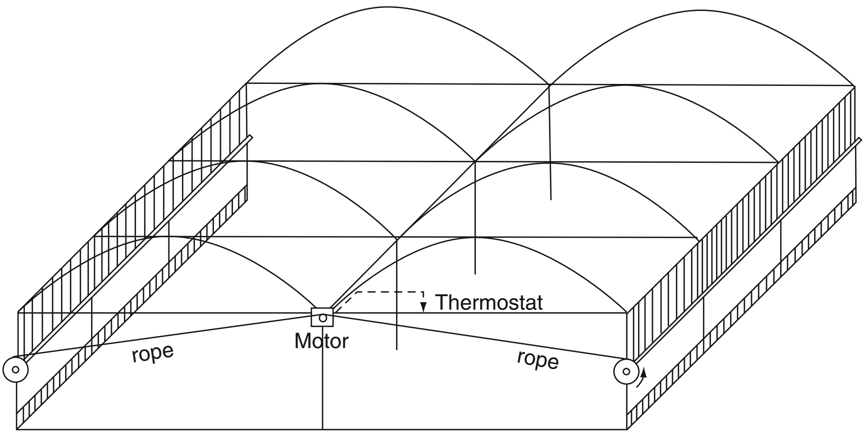
Figure 5.92 shows the material requirements of steel, aluminium, and zinc, which has been calculated by use of design drawings, parts lists and information from the manufacturer.

The glass greenhouses have the highest requirements of steel, and a relatively high amount of aluminium for purlins and bars. The amount of zinc for galvanizing depends on the surface of the steel components.

The energy requirements for the energy balance have been taken from the BUWAL study (1991). The energy and mass fluxes are calculated from raw material extraction to the end of the product, including transport and disposal. An energy amount of 7.6 kWh/kg is necessary for steel production, and an amount of 32.7 kWh/kg for the aluminium production, taking into account a recycling rate of 45% for steel and 35% for aluminium (Fig. 5.93).

The energy requirement for glass greenhouses is higher than for plastic-film greenhouses.

The energy equivalents for glass and low-density polyethylene LDPE are (Buwal1991):



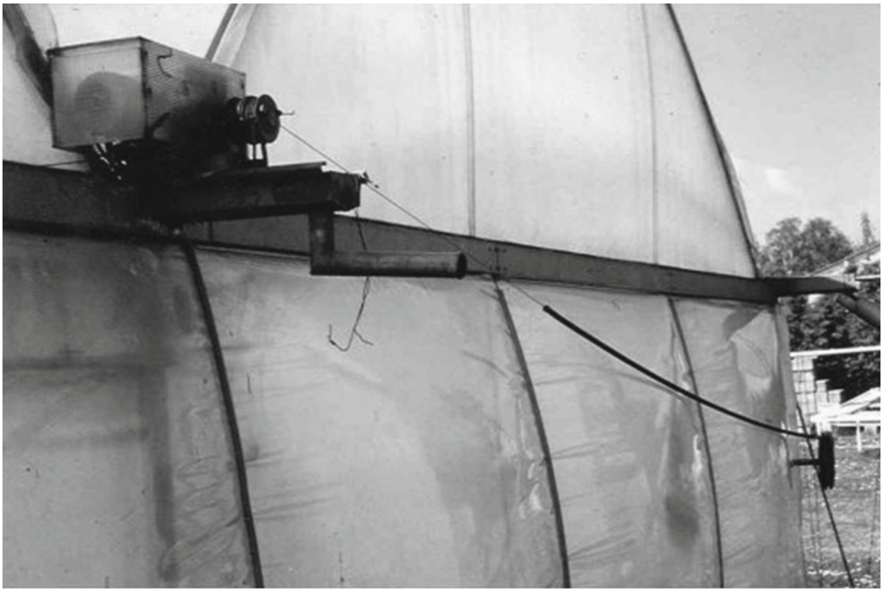



**Fig. 5.86** The roll-up ventilations on both side walls can be operated by one driving motor and controlled by a thermostat

| | |
|---|---|
| Glass (45% recycling) | 2.2 kWh/kg |
| LDPE (without energy recovery by burning) | 19.1 kWh/kg |
| LDPE (with energy recovery of 80% of waste) | 13.2 kWh/kg |

The energy requirement per kg of material is much higher for plastic material PE than for glass, but calculating the energy for 1 $m^2$ of greenhouse floor area reverses

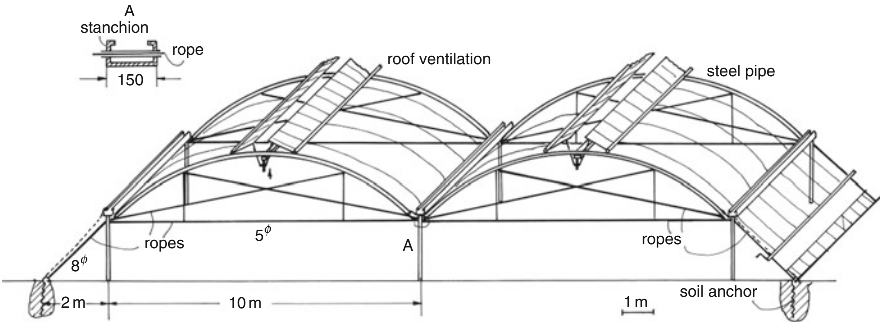



**Fig. 5.87** Australian design with inclined steel ropes at the side walls for stabilizing the structure. The plastic film will be rolled up at the inclined ropes for ventilation. The gutters and steel tubes inside the greenhouse are connected and guyed by ropes

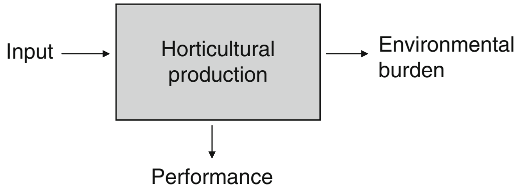



**Fig. 5.88** Valences of horticultural production

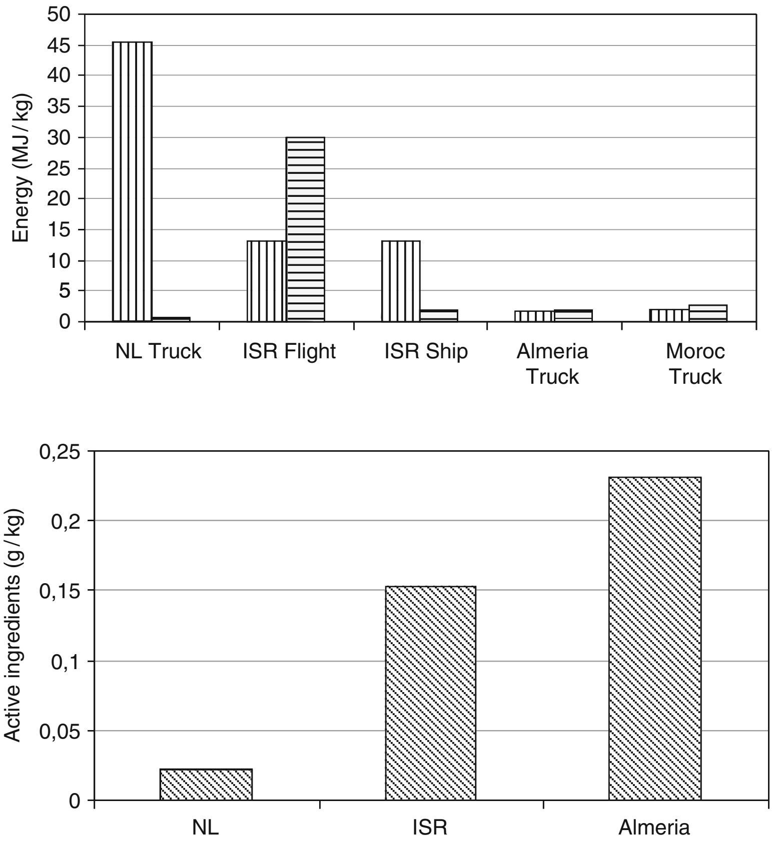



**Fig. 5.89** Consumption of energy and active ingredients for production and transport of tomatoes from different countries to Frankfurt in Germany (Verhaegh 1996). *NL* Netherlands, *ISR* Israel, *Moroc* Morocco

the conditions, because the material requirement for plastic film is lower than for glass (Table 5.11). The energy requirement for glass is about 22 kWh/m$^2$, and for single plastic film 5–6 kWh/m$^2$.

The energy balance for plastic-film greenhouses is more favourable than for glass greenhouses, in spite of the repeated changes of plastic film (Fig. 5.94).

Assumptions: 12-years life span of the greenhouses.

| |
|---|
| Glass: one cladding for 12 years |
| PE film: four changes in 12 years |
| Air cup film: three changes in 12 years |

The energy consumption for heating the greenhouses is much higher in 12 years than for manufacturing the structure. The percentage for manufacturing the

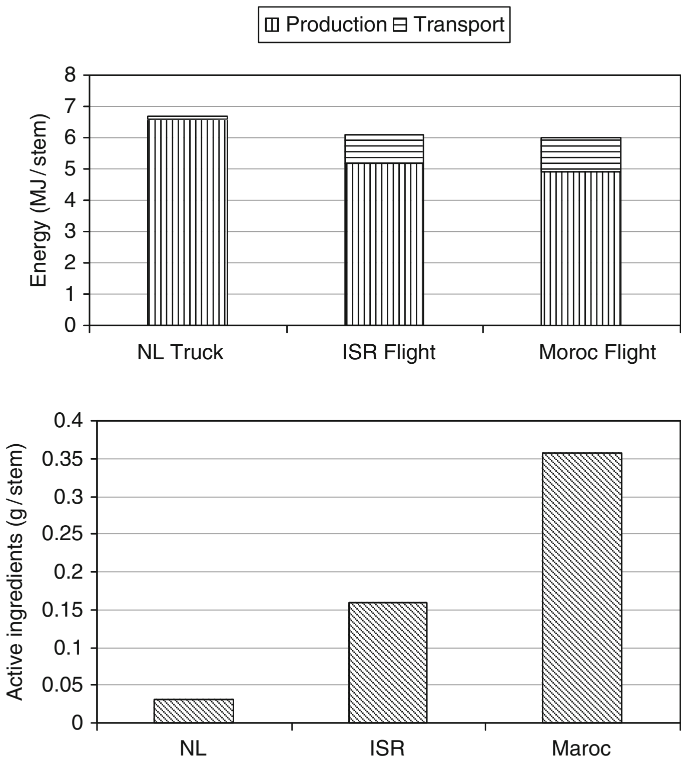



**Fig. 5.90** Consumption of energy and active ingredients for production and transport of roses from different countries to Frankfurt in Germany (Verhaegh 1996). *NL* Netherlands, *ISR* Israel, *Moroc* Morocco

structure is less than 3% for German conditions in comparison to the energy heating over 12 years.

The conclusion is: a higher amount of material for energy-saving measures, such as double-inflated plastic film and air cup film for plastic-film greenhouses results in much higher energy saving for heating (30–40%).

The water consumption for the production of steel and aluminium is 0.2–0.4 $m^3/m^2$ floor area. That is less than the irrigation water for 1 year.

Russo and Scarascia Mŭgnoza (2005) used the LCA method to compare greenhouse constructions:

A: Zinc coated steel and aluminium structure covered by 5-mm glass, life span 10 years. This greenhouse had the highest environmental impact.

B: Round-arched tunnel, zinc-coated steel covered by 200 µm PE plastic film, life span 2 years, five times recovered in 10 years. The environmental impact was remarkably lower than for the glass greenhouse.

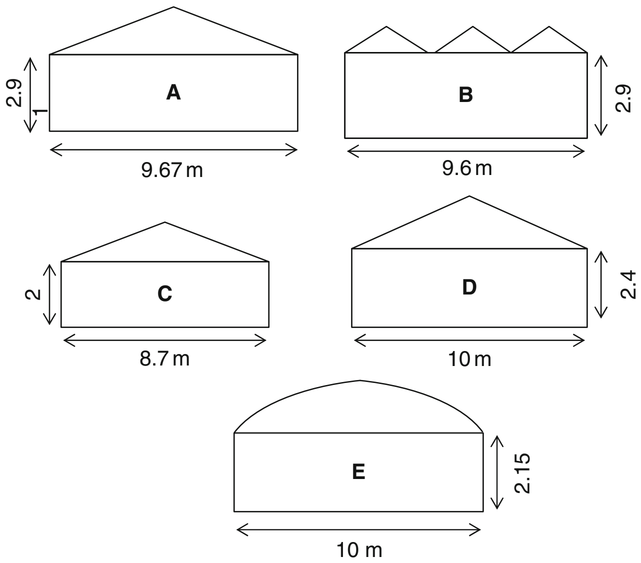



**Fig. 5.91** Greenhouse structure investigated by a mass and energy balance. Gutter heights in meters

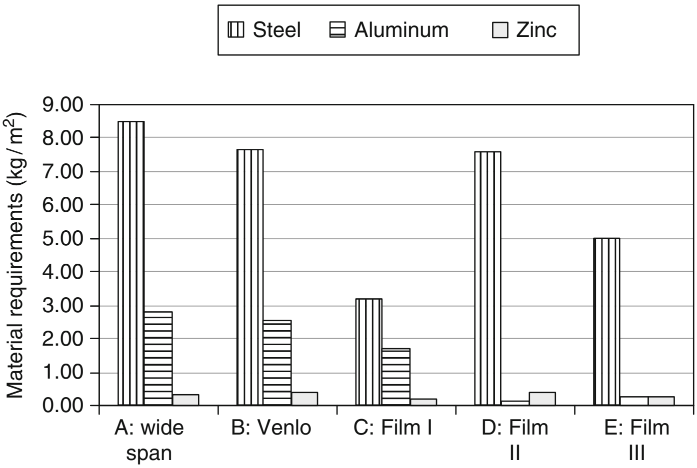



**Fig. 5.92** Material requirements of steel, aluminium and zinc per $m^2$ floor area of the different greenhouses

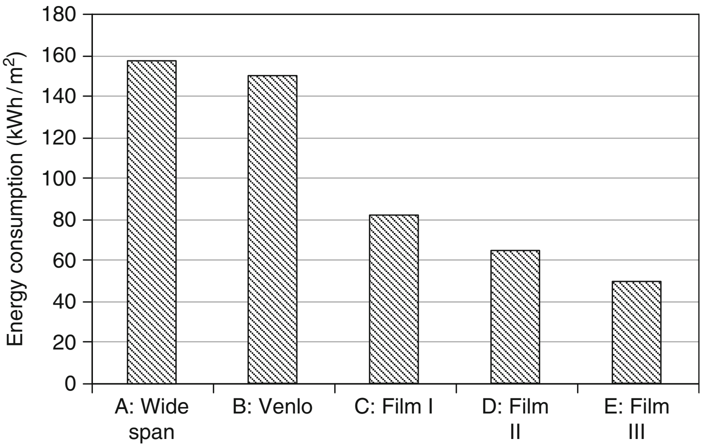



**Fig. 5.93** Energy requirement per $m^2$ floor area for the construction materials steel, aluminium and zinc of the different greenhouses

**Table 5.11** Material and energy requirements for greenhouse cladding materials

| | A: Wide span, glass | B: Venlo, glass | C:Film I, Single PE film | D:Film II, air cup film | E: Film III, single PE film | E: Film III, double PE film |
|---|---|---|---|---|---|---|
| Material (kg/$m^2$) | 10.2 | 10.0 | 0.32 | 0.66 | 0.24 | 0.48 |
| Energy for production (kWh/$m^2$) | 22.5 | 22.0 | 6.1 | 12.6 | 4.6 | 9.2 |
| Energy for production, minus 80% recovery (kWh/$m^2$) | | | 4.3 | 8.8 | 3.2 | 6.4 |

C: Chestnut wood structure, 5 years life span, covered by 200 μm PE plastic film. This greenhouse had the lowest environmental impact.

Three methods of cooling have been evaluated by using the LCA method (Anton et al. 2006) in three Parral-type greenhouses, 630 $m^2$ floor area each, with a sweet pepper crop:

- Forced ventilation by three fans,
- Fog system with high pressure nozzles,
- Whitewash shading.

The total production costs for sweet pepper of the forced ventilation system and the fog system were 51% and 13% respectively higher compared to whitewash, set to 100%.

The environmental impact due to $CO_2$ and $SO_2$ releases was about 14 times higher for the forced ventilation than for the fog system, due to the higher electricity consumption for forced ventilation.

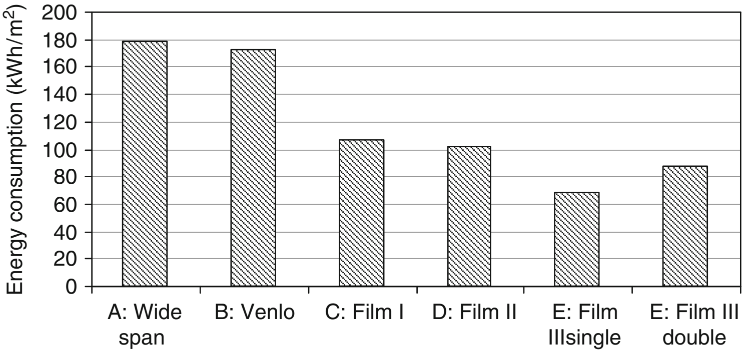



**Fig. 5.94** Total energy balance for the greenhouses in Fig. 5.91

The fog system could be justified from an environmental and economical point of view if the increase in production were 9 and 6% respectively higher in comparison to the whitewash. The forced ventilation system could not be justified in the Parral-type greenhouse.