AN OVERVIEW OF THE CONTRIBUTION OF WORLDVEG IN DEVELOPING PROTECTED CULTIVATION AND ITS USE OF INTEGRATED PEST MANAGEMENT

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ABSTRACT

Protected cultivation provides a favourable environment for both crops and their pests and diseases. The warm, humid conditions prevalent inside net-houses provide an environment that is more congenial and favourable to insect pests and diseases, and cultivation practices need to be well managed for protected cultivation to be successful. Robust and efficient pest management programs along with good crop and environmental monitoring to reduce the severity of pests and diseases. Entomologists, plant pathologists, horticulturists and agricultural engineers need to work closely together to assure that new techniques introduced under protected cultivation benefit crop health. Improved monitoring and decision systems need to be developed to assess the levels of pest incidence for proper management decision making. The design of suitable net-houses and plastic houses plays an important role in minimizing the entry of insect pests, and reducing pesticide use. The World Vegetable Center (WorldVeg) has played an important role in the promotion of protected cultivation in India, Pakistan, Bangladesh and Tajikistan by developing and promoting polynet houses and low-cost structures for seedlings and fresh produce, varietal testing under protected cultivation, the promotion of trickle irrigation systems and integrated management practices for insect pests and diseases under protected cultivation. This review focuses on the main components of protected cultivation from the design of structures, to integrated pest and disease management and how these have been implemented in practice, with a particular focus on India and Pakistan.

INTRODUCTION

Crops cultivated under protected cultivation require an extremely high level of management for proper growth and development. Crop protection activities using pesticides is a key part of this management. Pest problems are major threats under protected cultivations and the cost for their control increases under intensive protected cultivation by about 5% as compared to open field production (Gullino et al. 2002). Injudicious use of pesticides often leads to pest resurgence and insecticide resistance. To be economically viable, vegetable production under protected conditions must be more intensive than in the open field, focusing on higher value crops and generally using more external inputs. The warm, humid conditions, abundant food and a lack of natural enemies under protected cultivation create an environment which is more conducive to the establishment, spread and perpetuation of certain insect pests and plant diseases. Also, the extended, sometimes year-round, cropping cycles with repeated cultivation, often of the same crop species or plant families and rapid crop rotations (shorter break periods), promote the perpetuation and build-up of soil-borne insect pests, nematodes and diseases such as fungal and bacterial wilts. The predominant insect pests and diseases present may differ between the Kharif (autumn crop sown at the beginning of the summer rains) and Rabi (crop sown in September and harvested in the spring) seasons.

WorldVeg has been working on the management of insect pests of vegetables grown under net structures in South Asia for about a decade. Early net houses in Punjab were not able to cope with strong winds and many collapsed. A new net house design was introduced by WorldVeg in collaboration with Punjab Agricultural University (PAU), the State Farmers Commission of Punjab, National Taiwan University, and several net house manufacturing companies in Taiwan. These drew on Taiwanese designs capable of withstanding typhoons that are common there in summer. The 500 m² (62.5 m x 8 m) net-house was sturdier than local designs and protects vegetable crops from insects. To address the insect pests, soil-borne and foliar diseases, WorldVeg and PAU subsequently developed and validated a series of IPM methods for net house vegetable production.
TYPES OF PROTECTIVE STRUCTURES

Two general types of protective structures are used for the cultivation of crops under protected cultivation; permanent and temporary. WorldVeg along with partners has designed suitable net-house and plastic house structures with maintenance procedures to prevent the entry of all damaging insects, thereby reducing the need to use pesticides.

Permanent Net-houses

These net-houses can last for at least five years. The permanent structures being widely used is 2 m high made of galvanized iron tubing covered with nylon net (Talekar et al. 2003) (Figure 1). To exclude larger insects such as lepidopterans, the coarser net of 16- to 32-mesh size is used, while for smaller insects including thrips, whiteflies, and aphids, finer net (50- or 60-mesh size) is used (Talekar et al. 2003; Harmanto 2006; Shahak et al. 2008; Palada and Wu 2009). Coarser nets allow free flow of air with the minimum build-up of inside temperatures. A 500 m² net-house can produce up to 15 cycles of various leafy vegetables free of any pesticides with good yields and quality over a two-year period in Taiwan. Other crops including tomato, eggplant, cabbage, cauliflower, broccoli, yard-long bean, and bitter gourd can also be grown successfully in net-houses (Talekar et al. 2003). The proper design, location and construction methods are important to ensure pest-free crops.

![Figure 1: Improved net-house as designed for the climatic conditions in Punjab](image)

Plastic Houses

Plastic net-houses are permanent structures that can last for about four to five years. These are built using transparent but sturdy rainproof plastics and are used mainly for the cultivation of longer duration fruit vegetables such as tomato, sweet pepper, and cucumber. The plastic sheets protect the crop from rain and avoid insect entry into the net-house. A variety of designs can be used but plastic houses are commonly 25 x 26 m² in size (Figure 2). The roof may have a semi-circular top covered with clear plastic. Either ultraviolet (UV) stabilized plastic is used or the plastic is treated with a UV light protectant. In the centre, a 30 cm portion along the entire length of the semi-circular top of the plastic cover is closed with nylon netting to facilitate ventilation and reduce heat build-up inside the net-house. The open portion is made rainproof by providing a transparent plastic shade over the top. The side walls are covered with nylon netting.
Temporary Plastic Houses

Two types of temporary plastic house are used for a single growing season: a single-bed type with an arched roof and a double-bed type having an A-shaped roof covered with UV-protectant polyethylene film. For the single-bed and the double-bed plastic houses, the widths are 2.4 m and 4.8 m, respectively. At the centre, the height of both types is 2.4 m (Palada et al. 2003). Nylon netting is used to cover the sides to exclude insect pests and to prevent rain from entering. These structures have significantly improved the growth and yield of cucumber, sweet pepper, and small-headed cabbage in Vietnam, while significantly reducing the incidence of fungal and viral diseases (Hanh 2003).

Low Net Tunnels

Farmers who cannot afford the high-cost permanent plastic houses or net-houses can use temporary low-cost low tunnels (Figure 3). These tunnels are constructed with U-shaped iron or aluminium bars covered with nylon netting over each bed (Talekar et al., 2003). The nylon nets prevent the crops from insect pests and heavy rain, thus reducing the number of insecticide sprays. These structures can be used for the cultivation of leafy vegetables such as Brassica rapa var chinensis, B. oleracea var. alboflabra, B. rapa var. parachinensis, and B. juncea. Under net tunnels, the yield of Amaranthus has been tripled in Vietnam (AVRDC 2004). Cauliflowers cultivated under net tunnels in Cambodia had 80% less insect pest populations and yielded 1.5 to 2.0 times greater than in the open field (Palada and Ali 2007). Head cabbage grown under net tunnels in the Solomon Islands reduced insect incidence by 38-72% and significantly increased the economic returns (Neave et al. 2011).
New Design Net-house

The new design developed by WorldVeg and PAU is more stable than the older designs (Figure 4). This design has a deeper foundation, uses hoops as trusses, employs tension wires, and has a double-door arrangement and withstands the pressure of the covering material, intense rain, and high winds (Srinivasan 2011). Furthermore, during winter (December-January), plastic sheeting can be attached to create a more favourable temperature for better vegetative and reproductive growth. In summer (May-June), this can be replaced with shade net for protection from heat. The net should be constructed in an east-west direction to provide maximum exposure to sunlight throughout the year and minimize the adverse effect of wind.

In addition, the net house should be free of shading and should be located away from a distance of at least three times the height of any nearby obstruction. Windbreaks (tall plants, buildings, etc.) should be at least 30 m away on all sides. There are a variety of methods for sterilising the soil, but one is to use flooding to sterilize the soil to remove the soil-borne insect pests. An extra 2-m-wide border should be included along all four sides and the entire area should be flooded with 15 to 25 cm standing water continuously for 4 to 7 days. The area should be puddled with suitable farm equipment, if feasible, to kill insects, some pathogens, nematodes and weeds in the soil. The water should be drained after 4 to 7 days of flooding and the area allowed to dry. Care should be taken that no weeds grow before the construction of the net house to ensure that no plant-feeding insects or mites are in the area.

The Double Door System

Insects easily enter through net house doors. It is very important to reduce the entry of insects from outside into the net house. Early designs of net houses had only one door that would allow easy entry of insects while opening. Gaps between the door panel and soil surface can also provide openings for insects to enter. Farmers need to avoid the habit of keeping doors propped open while they are working inside. The double door system restricts the entry of insect pests. The double door system has two doors that open on opposite sides. The doors should be placed in such a way that one door cannot be opened before closing the first one, whether the farmer is entering or exiting the net house (AVRDC 2007). In a double door, the front and back frames are constructed using MS square pipes. The front side is attached to a net room 1 m x 1.2 m x 2 m as the double door entry point. The doors must be perpendicular to each other and are constructed as shown (Figure 5).
The netting for constructing a net house should have small size holes (40- or 64-mesh). The air does not flow readily through small mesh nets and increases the temperatures inside the net houses. With finer nets sunlight transmission is also reduced; dust particles blown by the wind block the holes and prevent sunlight from passing through. A uniformly woven 50-mesh net of good quality will prevent the entry of most vegetable insect pests. However, some red spider mites and thrips may be able to pass through the net of this size. The net should be attached at the top of the side pillars of the structure using poly-grip assemblies so that it will not be blown away by the wind. The net should be stitched vertically to reduce the pressure on the seams and to avoid tearing of the net. The net should be fastened using the poly-grip assembly. During winter and summer, poly-sheets should be attached in the same assembly.

MANAGEMENT OF DISEASES AND INSECT PESTS IN NET HOUSES

Raising Healthy Seedlings

Healthy seedling production is very important for a healthy crop. Healthy seedlings assure the establishment of vigorous plants free of insects and disease in net houses. For healthy seedlings, improved quality seed should be used. The seeds should be treated with fungicides such as thiram or captan at the rate of 2-3 g per kg seed to protect them from soil-borne fungal pathogens. Seeds should also be treated with imidacloprid or thiamethoxam for the management of soil borne and sucking insect pests. Seeds can also be treated with some biocontrol agents like Trichoderma viride, T. harzianum, Pseudomonas fluorescens, and Bacillus subtilis. These protect the germinating seeds from soil-borne pathogens, promote plant growth, and induce resistance against diseases. Biocontrol seed treatment should always be applied after chemicals and before insecticides.

The seedlings should be raised in plastic plug trays with the correct cell/hole size (Figure 6). For tomato, eggplant and peppers, the trays with 4 cm deep and 4.5 cm diameter cells should be used for raising the seedlings. Cucurbit crops require a larger cell size than other vegetable crops. The trays should be disinfected with 1% solution of chlorine bleach and rinsed thoroughly with clean water before use. The seedling mixture should consist of cocopeat, perlite, and vermiculite in a 3:1:1 ratio. A mixture of compost, sterilized rice hulls/husks and sand in a ratio of 3:1:1 also can be used. The mixture should have a pH of 5.5-6.5 to improve micronutrient availability. The growing medium should have good drainage. The tray holes should be filled with the pre-moistened growing mixture.

One to two seeds should be sown in the centre of each cell, about 0.5-1 cm deep, depending on the size of seed sown. The seeds should be covered with the same potting mixture. After seed sowing, the seedling trays should be placed on 1 m high iron benches and covered with 50-60 mesh size nylon net, using 2 m wide and 1 m high inverted ‘U’-shaped iron/aluminium bars to support the net (Figure 7). If benches are not available the trays can be placed on raised beds to keep the trays above ground level. In summer, green shade net, and in winter, polythene sheet covers should be used to protect the seedlings from high and low temperatures, respectively. The netting covering the nursery should be tightly buried under the soil so that no gaps are left between soil and the net that would allow the entry of pests. Polythene sheets also protect the seedlings from rain and frost. Seedlings should be watered at the rate of 15 ml per hole during the first week and subsequently at the rate of 7.5-10 ml per hole daily. During high temperatures, watering can be done twice a day. Irrigation should not be done in the afternoon as it keeps foliage wet for a longer time rendering the seedlings vulnerable to diseases.
Figure 7: A moderately simple net-house with raised benches and concrete floor for producing seedlings in plastic plug trays.

Insect pests such as thrips, whiteflies and aphids, which cause direct damage by sucking plant sap and indirectly by transmitting viral disease, can be controlled by installing sticky traps, yellow (for whiteflies, aphids, leafhopper and leafminers) and blue (for thrips) in the nursery. Seeds should be treated with insecticides, fungicides and/or bio-control agents including antagonistic fungi to prevent damage by insect pests and seed borne diseases.

Proper fertilizer application is important for the crop development. The application of a higher proportion of nitrate nitrogen (NO₃) than ammonium (NH₄) and increasing the soil pH by liming reduces the incidence of Fusarium wilt in vegetables. Also, adequate calcium is necessary to minimize blossom end rot and to provide for overall healthy growth.

The seedlings should be hardened to minimize the transplanting shock by moving them outside for 2 to 3 days to acclimatize before transplanting. Seedlings that are adequately hardened recover and establish well when transplanted in well-irrigated beds. For transplanting, the plug trays should be drenched with water a day before transplanting to ease uprooting of the seedlings.

Insect and Disease Management in the Established Crop

Weeds are important alternative hosts of insect pests and pathogens. Weeding should be done in and around the net house to help minimize disease and insect population build-up. Overhead irrigation should be avoided, as it results in prolonged leaf wetness, thereby encouraging disease development. The net-house doors should be tightly closed at all times. Insects may enter through the gaps of the doors and infest the crop. The net-house should be inspected frequently for any net damage. Holes and tears should be repaired promptly to make sure no insects can enter. Garden tools such as shovels, secateurs, spades, picks, hoes, machete, rakes, sickles, axes and shears should be disinfected by washing them with detergent or 20% household bleach. Field labours working in insect-infested or diseased crop should not enter the net-house as they could be carrying insects or pathogens with them. Proper spacing, training and pruning are highly important for good air circulation between the plants and that can assist in reducing disease infestation. Plant debris that is infested with insects or disease must be discarded in a dump pile well away from the production site, as plant pathogens and insects can remain viable in plant debris. The crop should be monitored on alternate days to check for the incidental entry of insect pests. The eggplant leaves and fruits infested by eggplant shoot and fruit borer, Helicoverpa spp., Spodoptera spp., Epilachna beetle or leaf miner should be removed and destroyed immediately. Further, egg masses of common armyworm and the larva of other insect pests should be destroyed manually. Pheromone traps can be used to monitor and mass-trap the insect pests. Application of biocontrol agents like Trichoderma spp., Bacillus subtilis, Pseudomonas fluorescens, , B. thuringiensis, and neem formulations help minimize the population of soil-borne and foliar pathogens as well as some insect pests. Straw or plastic mulches reduce whitefly incidence. Broad spectrum insecticides should be avoided.

The important pests of solanaceous crops under protected cultivation include thrips, whiteflies, mites, aphids, leafminers, mealybugs, Tuta absoluta, Helicoverpa spp., Spodoptera spp. and Epilachna beetle.

**Thrips** are very difficult to control under protected cultivation. They are tiny insects that reproduce rapidly and congregate in tight places that make pesticide coverage difficult. They suck sap from flowers and leaves, deforming them and are a major source of transmitting tospovirus diseases.

**Whiteflies** are serious pests in protected cultivation, feeding on the lower sides of leaves causing them to dry-up prematurely and reducing yields and contaminating crop products with honeydew. They also transmit
geminiviruses, which can lead to 100% yield loss, if the crop is left unprotected (Berlinger and Lebiush Mordechi 1996).

**Mites** are serious pests of tomato, pepper and capsicum under protected cultivation. The incidence of mites increases with high temperature and high humidity. They suck the plant sap and cause a mottled appearance, leaf loss or even death of the plant. Plants grown at high temperatures in dry protected cultivation are more prone to infestations.

**Aphids** are small, soft-bodied, sedentary insects and can be seen in colonies on the leaves, stem and flowers of the host plants. Aphids suck plant sap from the tender parts and multiply rapidly. The stem and leaves curl. They also secrete honey dew on which black sooty mold develops. They also spread viral disease.

**South American tomato leaf miner. Tuta absoluta** has recently emerged a major pest of tomato and other solanaceous crops such as chilli, potato and eggplant both in open field and under protected cultivation. It can cause losses of 80-100% on tomatoes in both protected cultivation and open fields (Illakwahhi and Srivastava 2017.). It can be spread by seedlings, infested vines and through tomato fruit and used seedling containers (Figure 8). Since tomato leaf miner does not fly well, most spread is facilitated by people transporting infested plants including seedlings, fruit or equipment. So the first step is to try to minimize the spread of local infestation. Tomato leaf miner can be readily brought in on seedlings or fruit grown in infested areas. If the pest arrives in a late larval stage or as pupa it can develop into a moth at the packing station. Crates returned to tomato producers from packing operations should be sterilised before being returned and workers should be vigilant in cleaning or disposing of all packaging which may have contained infested fruit. Any vehicles that have been used to transport such fruit should also be cleaned to limit the possibility of spread.

![Figure 8: (a) Tuta infestation, (b) mealybug infestation, under protected cultivation](image)

These features make proper management of protected vegetable production difficult and knowledge-intensive since it requires an integrated, but adaptable, approach across all the production activities from variety selection through to crop nutrition and watering and even crop (and worker) hygiene and phytosanitation. Unless farmers react quickly, a pest problem can rapidly get out of hand. Pesticide use to control them is often excessive but can be minimized with training in integrated pest management that combines cultural, mechanical, biological or even chemical controls. Without good crop management, losses due to pests and diseases in protected cultivation can be extremely high, including the loss of entire crops.

The integrated pest management (IPM) technologies developed by WorldVeg offer good alternatives to curb insect pests and pests. IPM is a systematic approach and focuses on long-term prevention or suppression with minimal impact on human health, the environment, and non-target organisms. It includes all reasonable measures to prevent pest problems by properly identifying pests, monitoring population dynamics, and utilizing cultural, physical, biological, or chemical control methods to reduce pests to acceptable levels. Farmers increasingly are adopting these safer methods of pest control.

**Successfully Implementing IPM**

Successful implementation of an integrated pest management strategy for protected cultivation of vegetables such as tomato, capsicum or cucumber depends on the following strategies to be implemented in cooperation with key farmers, working with farmer groups in a collaborative learning approach before, during and after the main cropping season, modifying protected cultivation structures and local practices as needed, and focusing on these following issues:
Educating farmers about IPM based approaches: These need to involve demonstrations, visits throughout the season, discussions between farmers, developing online sharing of pest alerts, technical advice and success stories.

Promoting healthy seedling production: Good insect control in polynet houses and in the field begins with healthy seed and seedlings. Treating seeds or seedlings with systemic insecticides including botanicals such as neem confers significant protection from early season sucking insects, and farmers need to understand that insect control begins with healthy seedling production practices.

Using sticky traps in polynet houses: A range of coloured sticky traps can provide very economical monitoring and control of insect pests right from just after germination through to fruiting and can keep sucking pests and leafminers under control.

Netting and Plastic covers: The size of netting has an impact on which pests are kept out, and it is essential to prevent holes or allowing insect entry through open doors. The type of UV absorbing plastic roofing can also affect the suitability of the environment for pests. Reflective mulches can also be used to keep the insects away from the crops by disorienting them.

Enriched/Fortified/Suppressive compost: The compost used in the poly net-house can either reduce or exacerbate an insect pest problem. When the compost is mixed with antagonist fungi such as Trichoderma or entomopathogenic fungi such as Metarhizium anisopliae or Beauveria bassiana, they suppress the development of soil-borne diseases and plant pests.

Polynet house Sanitation: Keeping the area around polyhouses clean and free from weeds or other alternate host plants, and managing as much as possible the crops grown in the vicinity can have a large impact on reducing sources of infestation.

Use of pheromone traps for monitoring and mass trapping of Tuta: These can be used both for monitoring pest numbers and reducing them, particularly if limited numbers are found in protected cultivation. Open field trials of these by WorldVeg in Karnataka found that major reductions in damage could be achieved. Using pheromone traps in nurseries and just after transplantation plays an important role in managing Tuta. They can also be used for mass trapping of male insects to reduce populations under protected cultivation, especially if insect exclusion nets and tight doors are used. It is highly effective when used along with other control measures to reduce the damage and reliance on insecticides.

Mating disruption techniques: This involves high applications of pheromones to a limited area to prevent mating and is particularly suited to protected cultivation. Here many source points of pheromones are used to confuse the males.

Disease Management for Vegetables under Protected Cultivation

To be economically viable, vegetable production under protected conditions must be more intensive than in the open field, focusing on higher value crops and generally using more external inputs. The protected conditions and higher planting densities generally make a warmer and more humid environment which is more conducive to the establishment, spread and perpetuation of certain diseases (and pests). Also, the extended, sometimes year-round, cropping with repeated cultivation, often of the same crop species, and rapid crop rotations (shorter break periods), promote the perpetuation and build-up of soil-borne nematodes and diseases such as fungal and bacterial wilts. The predominant diseases present may differ between Kharif and Rabi seasons. These features make proper management of protected vegetable production difficult and knowledge intensive since it requires an integrated, but adaptable, approach across all production activities from variety selection through crop nutrition and watering, and even crop (and worker) hygiene and phytosanitation. Without good crop management, losses due to pests and diseases in protected cultivation can be extremely high, including the loss of entire crops.

The most common diseases in protected cultivation of Solanaceous vegetables are:
- Tomato (bacterial leaf spot, damping off, bacterial wilt, early blight, leaf curl (kharif season), in Rabi season bacterial leaf spot, powdery mildew), capsicum (damping off and wilt, die back, anthracnose, leaf curl, Bacterial leaf spot in both seasons and cucumber (powdery mildew, downy mildew and Fusarium wilt).

Selection and promotion of resistant varieties: Wherever possible this is the simplest and most effective solution, but requires working with nurseries, trailing a range of lines to assess local disease resistance and ensuring that seed is available. There are increasing numbers of virus and disease resistant lines of major vegetables that WorldVeg has developed which can provide viable cropping options for farmers. These and commercial lines can be tested to assess which options provide the best disease management.

Seed and seedling treatments and good seed bed and seedling nursery management: Seeds can be washed (e.g. 10% Trisodium phosphate dip for 1hr) to remove surface contamination with viruses, viroids or bacteria. They can then be treated with biological agents (e.g. Azotobacter, Pseudomonas fluorescens or Trichoderma harzianum) that enhance the nutrient uptake and outcompete pathogens. Seeds should be sown in a pathogen and nematode-free soil/compost mixture in a net cage to keep virus vectors (e.g. whiteflies, aphids, thrips) off
the young seedlings while they are most vulnerable to infection. Seedling roots can be dipped in a persistent, systemic insecticide (e.g. imidacloprid) at transplanting to protect them from whitefly, aphid or thrips-transmitted virus infection for the first few weeks of growth.

**Grafting using pest resistant root-stocks:** This works best for controlling root diseases and root-knot nematodes, but also may provide some systemic acquired resistance to some foliar pests and diseases. Resistant rootstock accessions for tomato and pepper grafting have been identified by WorldVeg and are available for testing for adaptation to local conditions.

**Maintaining soil health:** Following a good pattern of crop rotation and avoiding growing the same species repeatedly in the same location will help prevent the build-up of soil-borne pathogens and nematodes. Including Indian mustard or marigold in the rotation can be particularly beneficial in this respect, as can the addition of biological additives such as neem cake or mustard cake to the soil. Soil solarisation can also be useful for reducing populations of root-knot nematode (and other soil-borne diseases) since most chemical soil treatments (e.g. methyl bromide) are no longer permitted. Solarisation should be conducted for at least 6 weeks during the hottest part of the year by laying clear polythene sheets over the soil inside the protective structure after first irrigating. High soil temperatures over 45°C need to be maintained to a depth of at least 10 cm.

**Good crop nutrition:** Well-balanced nutrient supplies help create healthy crops that are better able to withstand pathogen attacks. Soil testing and trialling of both pre-emergent and foliar fertilizers can be important along with the incorporation of adequate good quality organic matter.

**Pesticide applications:** There are several fungicides and insecticides that can be used in protected conditions. However, because of the cost and the risks to the health of the farmers and the environment, and of unacceptable residues, these should be regarded as a last resort for use when cultural management options have failed.

### Managing Root-Knot Nematodes

Besides insect pest and diseases, root-knot nematode (*Meloidogyne* sp.) is another serious pest of vegetable cultivation under protected cultivation. Root knot nematode is a minute round worm which cannot be seen with naked eye. They are obligate endoparasites, complete most of their life cycle within their host roots, and survive in soil as eggs and also second stage larvae. It can cause damage to most of the vegetable crops like tomato, brinjal, okra, capsicum and cucurbits etc., by forming galls/knots on the root system. Mature females of root knot nematodes deposit eggs (up to 1000 or more) in a gelatinous matrix which protects the eggs from dehydration. Moderate temperatures of 16 to 27 °C are favourable for its development. The hot and humid conditions prevalent inside a net-house are favourable for the multiplication of root knot nematodes.

Plant-feeding nematodes move up to short distances from a few inches to few feet. Nematodes generally spread by the movement of infested soil, irrigation water, implements and infested planting material from one place to another.

The above ground level symptoms caused by nematode infestation in the root system are yellowing of foliage and wilting in patches. The infested plants look pale, undernourished, water deficient and generally during daytime show wilting. Infested plants bear under-sized and lower numbers of fruits. The most characteristic symptom of root-knot nematode infestation is the formation of galls or knots on the roots (Figure 9). Due to the formation of galls/knots on roots, the uptake of water and nutrients by the plants is affected. Multiple infections on one root result in a swollen and rough appearance. The infested roots become weak and more vulnerable for saprophytic fungal and or infections by bacterial pathogens. The combined effect of nematodes and other fungal pathogens causes severe loss to the crops.
Monitoring of root-knot nematode population, as well as severity, is very important for its management. The soil samples should be analysed directly (extracting and counting eggs and juveniles) or by observing root gall index on a trap crop. Sanitation and good cultural practices are the best preventive measures against nematodes. Nematode free seedlings and planting material should be used to prevent the crop from nematode infestation at the later stage. This can be achieved by soil treatment, seed treatment and nursery raising in nematode-free areas or by the use of healthy nursery raising techniques. The irrigation water should be free from nematodes. The infested plants should be removed and burned or destroyed away from the net-house to reduce the nematode build-up in the soil. The net-house area should be free from weeds to reduce the chances of nematodes harbouring in them. If the net-house area is endemic to nematodes, select and grow resistant varieties or use resistant rootstock for raising crops through grafting technology. The application of soil amendments like peat, manure, and composts—are useful for increasing the water- and nutrient-holding capacity of the soil, especially sandy soils. This will increase the water holding capacity and can lessen the effects of nematode injury. Likewise, more frequent irrigation can help reduce nematode damage. Soil solarisation and soil application of bio-pesticides like neem seed cake (20 g/kg soil), mustard oil cake (Kaur and Srinivasan 2013), Verticillium lecanii and Trichoderma spp. formulation are effective in managing the root-knot nematode problem in vegetables. Further, root dipping of seedlings in 0.03% dimethoate 30 EC for 6 hours before transplanting can reduce nematode infestation to some extent.

**Postharvest Crop and Net-house Care**

Immediately after crop harvest, the plant debris should be removed from the net-house and the soil should be cleaned by flooding or sterilisation (Figure 10). This helps to reduce the carry-over of pests and diseases to subsequent crops. The whole area inside the net house should be rototilled to loosen the soil before using it again.

Pressurized water can be used to clean the net from inside and outside the house. This will remove dust and insect eggs lying on the net and also help increase the transmission of sunlight.
Implementing IPM under Protected Cultivation in Punjab, India and Pakistan

Farmers in Punjab, India have been growing vegetables in net houses and low tunnels of varying structure and design for the past 15 years. The materials used in construction vary considerably in quality. Early designs that were not well built caused several problems (as discussed above). In strong winds, the net could be blown off, and the structural frame could even collapse. In some net houses, particularly those of older design, pest damage can be higher than in the open field. Pests can pass through the mesh if the incorrect mesh size is used, and move through the tears, gaps, or holes in the net. Thus farmers still use chemical pesticides to protect their vegetables inside these net houses, defeating one of the greatest potential benefits of these structures: producing pesticide-free vegetables. There has been a considerable development of protected cultivation in Indian Punjab over the last 15 years with many of the technical problems overcome. However, marketing problems continue to cause problems for farmers in India and farmers who work as cooperatives to improve their technical production skills, gain access to better quality inputs and produce both sufficient quality and quantity of produce to attract major buyers to pay a premium for their produce have been the most successful.

About five years ago WorldVeg took a number of the initiatives first developed in Indian Punjab and in collaboration with national partners developed an extensive program to develop and promote protected cultivation in Pakistani Punjab. This was done as part of the four-year Agricultural Innovation Program (AIP) funded by USAID. Pakistani Punjab made extensive use of high and low plastic tunnels to protect crops from winter cold but the use of polynet houses for production of vegetables throughout the year was much less developed.

The major activities were on improving protected cultivation in Khyber Pakhtunkhwa (KP), Punjab and Balochistan. In Pakistan, more than 36 species of vegetables are grown and consumed in summer and winter owing to the country’s diverse climate and geography. The vegetables commonly grown in in the mild climate of the hilly areas include pepper, tomato, cauliflower, coriander and carrot.

Although the area and production of vegetables have increased in Pakistan in the past, the demand for vegetables is also increasing. There is a need to expand the area under protected cultivation. WorldVeg in collaboration with provincial partners focused on technically improving the protected cultivation of vegetables for the benefit of farmers. This was achieved by the identification and development of best varieties and IPM practices. Varieties and hybrids of vegetables were tested under plastic covers at different locations according to soil and agroclimatic conditions in consultation with farmers, public-sector research institutes and seed companies.

Protected cultivation provides partial climate control to protect crops from cold and provides a more humid growing environment. The vegetables grown under protected cultivation during offseason with improved IPM packages were tomato, cucumber, sweet pepper, chilli, bitter gourd and vegetable marrow.

The best performing varieties were identified by extensive varietal testing under protected cultivation. Improved IPM practices and alternative crops were demonstrated. A total of 96 varieties/hybrids were demonstrated on the farm in 6144 farmers’ fields. The best performing varieties identified were five tomatoes (Sallar, Anna, Deenar Sandal and Sahil), three cucumbers (Waleed, Beauty Queen and Ramzan), two Sweet peppers (Extra-2 and Bonus), one Chilli (Golden heart) and four Vegetable marrows (Zara, Charisma, Ezra and Sanam).
Field surveys identified that farmers were using excessive amounts of pesticides. Over 1000 farmers participated in 50 training courses on IPM practices and the implementation of this learning was found to lower pesticide use in the targeted districts by 15-20 percent.

To maximize the year-round use of tunnel structures trials showed that off-season production under shade nets in summer could be very profitable for spinach (US$ 14,647 ha⁻¹) and coriander (US$ 15979 ha⁻¹). Drip fertigation systems under protected cultivation not only saved water (25-45%) and fertilizer (29-42%) but also helped to reduce the cost of cultivation, lowered humidity and the use of pesticides. As a result of these initiatives, the area of protected cultivation and its profitability was improved significantly.

Figure 11: Sweet peppers raised under walk in tunnel at Chevanda, Faisalabad

PROTECTED CULTIVATION WITH HIGHER ECONOMIC RETURNS

In Pakistan, plastic tunnels are used from October to April to produce off-season vegetables such as tomato, cucumber, and sweet pepper, but the tunnels are vacant from May to September. To maximize the use of tunnel structures year-round and to increase the supply of fresh vegetables, the production of summer spinach and coriander under green shade netting was studied at different locations. Thirty drip irrigation systems were installed by covering tunnels with insect net at 41 different locations in partner institutes and in farmers’ fields in KP, Punjab, and Balochistan.
Vegetable Value Chains

Vegetable value chains are limited by poor supplies of high-quality seed and poor handling of fresh produce. WorldVeg and partners focused on developing sustainable commercial production of vegetable seed and trials to reduce postharvest losses of fresh produce. A total of 41.3 tonnes of vegetable seed of onion, tomato, chilli, okra and peas was produced across the country in two consecutive years. A small onion threshing machine was provided to an onion growing association in Bunir. After its success, other projects placed major orders to deliver these machines in Sindh and Balochistan. Seed producing contract farmers have been linked with seed dealers in the project area. Postharvest and value-adding studies of fresh tomato, onion and chilli identified lines with improved shelf lives and showed which packing methods produced fewer losses and quality deterioration.
CONCLUSIONS

It continues to be a challenge to improve the resilience of agriculture to cope with harsh environments while providing for future demands for nutritious food. Protected cultivation as one means of doing this has gained great momentum worldwide. High-value vegetable crops such as capsicum, cucumber, tomato and melons grow well under protected structures. A wide variety of structures is used in different environments and seasons, including poly houses, shade nets and poly-tunnels. WorldVeg has played an important role in the promotion of protected cultivation in India, Pakistan, Bangladesh and Tajikistan by developing and promoting improved polynet houses and low cost structures for protected cultivation in India, Pakistan, Bangladesh and Tajikistan by developing and promoting improved polynet houses and low cost structures for protected cultivation, through the promotion of trickle irrigation systems and promoting improved management of insect pests and diseases under protected cultivation. While these initiatives have helped to make it practical to produce high-quality products from protected cultivation, a critical issue that remains is to assist farmers in marketing their produce effectively. Many vegetable markets in the region do not work effectively and do not permit farmers to gain the prices that their quality produce requires to be economic. Unless there is a premium for the high-quality produce that is produced with minimal pesticides under protected cultivation the extra effort that it requires will not be economic. Farmers need to be able to produce both the quantity and quality of produce to attract premium buyers. Having helped make protected cultivation technically feasible, it is now critical to work with local markets to help make it consistently profitable.

REFERENCES