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Protected cultivation of vegetables in global arena: A review

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ABSTRACT

Protected cultivation of high value vegetables and cut-flowers has shown tremendous potential during the last decade or so. With the progress of liberalized economy and the advent of newer technologies in agriculture, protected cultivation opens up avenues in agriculture hitherto not seen. These technologies are not only creating avenues at higher level but also to the growers with the smaller landholdings as the higher productivity levels retain economic relevance to agriculture. Protected cultivation is in a way precise, progressive and parallel agriculture encompassing virtually all facets of agriculture and rather under additional scrutiny of technical relevance to situations and grower and market economics. Since protected cultivation is a vast assembly of diverse aspects of agriculture, this review is an effort to bring its current status in global arena covering various components of this important and emerging field of horticulture. Apart from the status, technological components and methodologies, review also discusses principal vegetables like tomato, cucumber, capsicum and lettuce in brief, besides a good amount of treatise on key pests and plant protection strategies in greenhouses.

Protected cultivation or greenhouse cultivation is the most contemporary approach to produce mainly, horticultural crops qualitatively and quantitatively and has spread extensively the world over in the last few decades. Protected cultivation also known as controlled environment agriculture (CEA) is highly productive, conservative of water and land and also protective of the environment (Jensen 2002). The technology involves the cultivation of horticultural crops in a controlled environment wherein the factors like the temperature, humidity, light, soil, water, fertilizers etc. are manipulated to attain maximum produce as well as allow a regular supply of them even during off-season. By adopting protected cultivation technology, the growers can look forward to a better and additional remuneration for high quality produce.

About 115 countries in the world are into greenhouse vegetable production commercially (Table 1). The world scenario shows the area under protected cultivation to be nearly 623 302 hectares while total estimated world greenhouse vegetable production area is 402 981. Of the total world greenhouse vegetable area, soilless/hydroponic culture systems account for 95 000 ha (Hickman 2011). The advent of protected cultivation technology in India materialized during the early nineties, post globalization. In India, the area under protected cultivation is presently around 25 000 ha while the greenhouse vegetable cultivation area is about 2 000 ha. Faced with constraints of land holdings, rapid urbanization, declining crop production, declining biodiversity and ever increasing population, demand for food, especially vegetables has increased manifold and protected cultivation has offered a new dimension to produce more in a limited area. Today Dutch protected cultivation is one of the most intensive farming systems in the world with high levels of output by using the latest technologies (Goncharova 2004).

Designs, construction and operations

The greenhouse cultivation of vegetables, being an intensive activity, entails perfect planning and numerous phases of operation for its success. Greenhouse design varies depending on its location, whether in a desert, the tropics or in a temperate region (Jensen 2002). The highly controlled greenhouses sprang up initially in the temperate regions, as growing of vegetables in the freezing temperatures was impracticable (Albright 2002) while the simpler greenhouses provided minimal climatic control and helped in producing an economic yield of the vegetable crops (Enoch 1986). In the temperate regions of the world, glasshouses are preferred more while in other sub-tropics and tropics, 'shading effect' and 'windbreak effect' are provided by greenhouses. Rain shelters are the usual protective structures in the rainy tropical regions to avoid flooding (Garnaud 1987), whereas in the arid regions, the temperature and humidity inside the

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Table 1 Major greenhouse vegetable production areas of the world (>500 ha only)

Country	ha ('000)	Country	ha ('000)
China	81.0	Argentina	2.2
Spain	70.4	Chile	2.1
South Korea	47.0	Jordan	2.0
Japan	36.0	Belgium	1.6
Turkey	33.5	Russia	1.4
Italy	25.0	Germany	1.4
Morocco	16.5	Australia	1.3
France	10.0	Tunisia	1.3
Poland	5.2	Romania	1.3
Hungary	5.4	Egypt	1.2
Algeria	5.0	Canada	1.2
Greece	5.0	Bulgaria	1.1
Netherlands	4.6	Libya	1.0
Columbia	1.2	Serbia/Montengr.	1.0
Mexico	4.3	Lebanon	1.0
Israel	4.0	Brazil	1.0
Iran	4.0	United Arab Emir.	0.8
Palestine	3.3	India	0.7
Syria	3.1	New Zealand	0.7
Ukraine	2.7	United Kingdom	0.7
Ecuador	2.7	USA	0.7
Portugal	1.5	Moldova	0.5

Source: Hickman 2011

Table 2 Major vegetables grown in greenhouses across the world (Yield/ha in tonnes)

Country	Tomato	Pepper/ Capsicum	Cucumber	Lettuce
China	In China the area under Plastic Greenhouse Vegetable Cultivation is 2.5 million hectares, out of which 90% area is under vegetable cultivation (Chang *et al.*, 2011) and tomatoes, cucumber, peppers and eggplant are the major vegetables being grown under plastic greenhouse cultivation system and all 32 provinces are doing protected cultivation of vegetables.			
USA	484	100		
Netherlands	460	262	690	NA
Canada	463	258	530	334
United Kingdom	413	248	480	36
Finland	337	138	396	126
Russia	300	100		
Mexico	153	NA		
Syria	141	NA		
Spain	150	70	95	25
Israel	NA	100		
Turkey	106	104	105	NA
Nicaragua	NA	49		

Source: Hickman 2011, Chang *et al.* 2011

greenhouse provides an 'oasis effect' compared to the hot and dry heat outside the greenhouse (Sirjacobs 1988).

Agro-climatic location and site selection

Vegetable crops often need to be protected against a combination of weather conditions. In addition to protection against fluctuating temperatures, protection is also required against solar radiation, heavy rain, hail and strong wind. High standards will need to be placed on the type of soil, the soil profile and the location. Thus, selection of suitable location for greenhouse construction is of utmost importance. Greenhouses should be away from industrial and over populated areas. Leveled ground where the light intensity is at its maximum is the priority. But even if the greenhouse has to be constructed on a slope, care should be taken such that surface runoff is directed away from it. Ensuring proper drainage to a lower area is essential around the site. Adequate water supply and a power source should be available nearer to the terrain selected for greenhouse construction.

Greenhouse for vegetable production encompasses: glasshouse, polyhouse, insect-proof net house, low tunnel polyhouse, zero energy polyhouse. Protected structures are of different kinds, viz. open-ventilated; closed polyhouse with fan and cooling-pad system; shade net house; sloped roof, rain shelter etc. Greenhouse structures are of different kinds based on shape (lean to type, evan span type, ridge and furrow type etc.), utility (temperature and humidity controlled), construction (wooden, pipe or truss framed), covering material (glass, fibreglass, plastic-film). Plastic film covering materials are of different types such as acrylic, polycarbonate, fibreglass reinforced polyester, polyethylene film (Montero *et al*. 2005) and polyvinyl chloride film. Plastic glazed greenhouses have many advantages over glasshouses, the main one being cost. Plastic also is adapted to various greenhouse designs, usually resistant to breakage, lightweight, and fairly easy to use. Most greenhouse crops grow best in light whose wavelengths range from 400 to 700 nanometers and hence the glazing materials should be highly transparent.

Production technologies

Vegetables can be produced in greenhouses under different methods which include planting in the greenhouse soil directly and the latest technique of hydroponic cultivation which involves either planting in different soilless mixtures using containers or using liquid nutrient media.

Soil and its management: The conventional method of growing vegetables in greenhouse involves planting directly into the well drained existing soil. Continuous cropping of the same crop over a period of time might totally destroy the soil structure in the greenhouse. Moreover, soil-borne pathogens and pests become a major concern if they get established in the closed structures. Hence, to maintain the soil structure enough care should be undertaken. Soil preparation entails initial practices like sanitation, solarization, mulching or fumigation. Apart from the major benefit of solarization in reducing soil-borne pathogens by soil-heating effects, many other possible additional beneficial effects also exist, as increased growth response (IGR) of plants consequent upon control of weeds and insect pests and as a bioremediation tool for pesticide polluted soils (Sesveren *et al.* 2011, Fenoll *et al.* 2010, Katan 1987, Katan *et al.* 1976). Solarization along with other control methods in an integrated way will attribute more benefits. Improving soil structure and replenishing its fertility by incorporation of manure, compost, and other organic amendments ultimately increases the soil microbial activities and nitrogen uptake by the plants and reduction of certain soil-borne diseases resulting in higher yields (Ge TiDa *et al.* 2011, Gelsomino *et al.* 2010, Michel and Lazzeri 2010, Abbasi *et al.* 2005, Maruo *et al.* 2002, Padmodaya and Reddy 1999). Soil testing must be carried out to determine the soil fertility and the deficiency of nutrients must be supplemented as and when required. The application of bioagents helps in not only managing many soil-borne pathogens including nematodes but also promotes plant growth (Cakmakci *et al.* 2006). An integrated approach of cultural practices will attribute more benefits in the long run.

Seedling production: Plant propagation requires an understanding of how dormant seeds germinate in the soil of their natural environment. Besides, it is important not only to ensure health of the nursery through proper fertigation but also monitoring of growth through hormonal treatment, proper media sterilization and greenhouse management for virus and pest free nursery. The plug-tray nursery raising technology is currently being used in most of the situations to produce disease-free, vigorous and off-season seedlings. Though cocopeat is the main substrate used in nurseries, but its extraction being an environmental concern has led to its replacement with other substrates with equal effect (Gezahegn *et al.* 2011, Vaughn *et al.* 2011). Sterilized, soilless growing media mostly comprising coco-peat, perlite and vermiculite in the ratio of 3:1:1 with addition of hydrogel, biological agents and organic amendments not only helps in raising high density seedlings but also evades soil-borne diseases (Sabir *et al*. 2011, Walia 2005) and some insect pests (Jovicich *et al*. 2009). The type and ingredients of soil-less media used for nursery raising have been standardized. Seedlings are watered when necessary and liquid fertilizer is applied based on leaf colour and growth analysis. The optimal inclusion of nutritional supplement and correct pH of the growing substrate ensures the seedling sturdiness and uniformity (Litvinov 2006, Mamatha and Baghyaraj 2002). Main advantage of this system is vigorous root development that minimizes mortality during transplantation. The technology provides a package of processes required to raise healthy nursery in a given time frame and providing protection against biotic and abiotic stresses to obtain a healthy crop ultimately.

Soil-less cultivation: Soil degradation, over-fertilising or soil-borne diseases in greenhouse systems required frequent replacing of greenhouse soils which ultimately paved the way for soil-less cultivation where different local materials like rockwool, peat, perlite, coconut fiber were used as substrates. Recent developments in soil-less cultivation refers to hydroponic cultivation which resorted to the use of either an aerated nutrient solution or an artificial soil composed of chemically inert materials (peat moss, coir, sand, sawdust, rock wool, perlite, vermiculite) moistened with nutrient solutions (Withrow and Withrow 1948). This method of greenhouse cultivation is mostly followed in developed countries and is very expensive. Of fertilizers applied commonly to the soil, only nitrogen can be recovered totally, but in hydroponics, all the nutrients provided to plants can be retained. The reuse of drainage nutrient solution in hydroponically grown greenhouse crops is very much essential to prevent environmental pollution. Hence, to recycle the nutrient solution, it is crucial to disinfect the drainage solution prior to reuse (Runia 1995). Thorough knowledge about plant physiology, growth habits and nutrient requirements should be known to the growers for adopting hydroponics, it requires intense monitoring. In future all systems are likely to be closed, with no drainage, preventing any loss of mineral elements and the contamination of groundwater (Jensen 1997).

Irrigation and fertigation: As compared to open field conditions, efficient water usage can be achieved through protected cultivation (Stanghellini 1992). Drip irrigation technology has come to stay in greenhouse production systems and it not only helps in using water efficiently but also can be responsible for reducing diseases that develop in rather moist conditions. Fertigation, i e irrigation combined with fertilizer application, requires consideration of plant needs, soil properties and technological requirements. It allows a precise and homogeneous application of nutrients in the area where the active roots are concentrated. The high potential efficiency of fertigation results from the possibility of using the optimal concentration of nutrients and a high density of roots in the moistened soil zone (Bar-Yosef and Sagiv 1982, Bravdo 1993). The concentration of the various nutrient elements in the irrigation water is necessary to achieve this objective which is also the main requirement to protect environment (Sonneveld *et al.* 1991). The understanding of plant growth behavior including nutrient requirements and rooting patterns, soil chemistry (solubility and mobility of the nutrients), fertilizers chemistry (mixing compatibility, precipitation, clogging and corrosion) and water quality factors (pH, salt and sodium hazards) is required for effective fertigation (Imas 1999). The quality of greenhouse vegetable crop improves in all respects such as fruit size, TSS content, ascorbic acid content and pH (Mahajan and Singh 2006). With fertigation through the drip irrigation system, crop

Table 3 Fertigation scheduling in vegetables under protected cultivation

Crop	Spacing (m)		Plants No/	Dose* (ppm)			Total (kg/1000 m^2)			Yield
	Plant to plant	Row to Row	1000 m^2	N	P	K	N	P	K	(q/1000 m^2)
Tomato	0.45	0.4	2 773	100-250	50-80	100-250	35	12	39	150-200
Cherry tomato	0.45	0.4	2 773	100-250	50-80	100-250	35	12	39	30-40
Capsicum	0.3	0.4	4 160	100-220	50-100	100-220	32	15	36	40-50
Cucumber	0.3	0.4	4 160	120-220	60-80	120-240	10-16	4-7	11-18	30-40

*Dosages vary depending upon varieties/ season/ crop stage.
Source: Hasan *et al*. 2010

foliage can be kept dry thus avoiding leaf burn and delaying the development of plant pathogens. Depending upon different varieties, season and crop stage fertigation schedule for different vegetable crop varies (Table 3).

The observed effects of foliar fertilization have included yield increases, resistance to diseases and insect pests, improved drought tolerance, and enhanced crop quality (Menzies *et al*. 1992, Reuveni *et al*. 1995, Reuveni *et al*. 1997). Plant response is dependent on species, fertilizer form, concentration, and frequency of application, as well as the stage of plant growth. Awareness of the nutritional status of all the components of a soilless culture system is vital to judge the success of the fertigation management practices to diagnose nutrient deficiency and correct symptoms that may occur (Johnson 2008). The yield reductions at low frequency irrigation (and fertigation) results from nutrient deficiency, rather than water shortage, and high irrigation frequency can compensate for nutrient deficiency (Silber *et al*. 2003). High levels of salinity in the nutrient solution reduces the plant growth and final yields, hence a balance between these factors should be maintained (Stanghellini *et al*. 2005). Specific fertigation programmes based on the basic nutrient solution required for some greenhouse crops have been developed (Voogt 2005).

Table 4 Composition of the basic nutrient solution for fertigation for some greenhouse crops

Crop	Nutrient solution mmol/L					
	NH$_4$					
Tomato	0.4	K	Ca	Mg	NO$_3$	SO$_4$
Cucumber	0.9	5	2	1.5	9.4	1.5
Sweet pepper	0.4	3.5	2	1	8.4	1
Rose	0.9	5	2	1	8.4	1

Source: Voogt 2005

Macro-nutrients	ppm	Micro-nutrients	ppm
N	105	Fe	2.3
P	33	B	0.23
K	138	Mn	0.26
Ca	85	Zn	0.024
Mg	25	Cu	0.01
S	33	Mo	0.007

Calculated as per Johnson 1980

Soilless culture often termed as solution culture is a way of providing support and a reservoir for nutrients and water to plants. Soilless culture methods may be categorized as either solid or liquid-medium systems. Solid-medium soilless culture may utilize any suitable media that has a uniform texture which drains well yet retains some nutrients and water provided. This medium is usually lightweight, the simplest, most economical and easiest to manage of all soilless systems. The most common types of media used in containerized systems of soilless culture are peat-lite (Boodley and Sheldrake 1977) or a mixture of bark and wood chips.

Liquid systems also called 'hydroponics' are generally closed circuit with respect to nutrient-solution supply wherein the solution is re-circulated continuously or intermittently for a period of days or weeks. Fertilizer programmes for soilless-culture systems must supply all nutrients required by the plants. Carbon, hydrogen, and oxygen are provided from water and carbon dioxide in the air while nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, boron, copper, zinc, manganese, molybdenum, and chlorine are supplied by the grower. Liquid-medium systems—such as NFT and gravel-bed culture—use complete nutrient solutions prepared from soluble inorganic salts containing various elements. Commonly used chemicals for the macronutrients include potassium nitrate, calcium nitrate, potassium phosphate, and magnesium sulfate. Micronutrients that are typically and essentially incorporated in the hydroponic solutions include Fe (iron), Mn (manganese), Cu (copper), Zn (zinc), B (boron), Cl (chlorine), and Ni (nickel) (Johnson 1980).

Good Agricultural Practices (GAP)

Good Agricultural Practices (GAP) are "practices that address environmental, economic and social sustainability for on-farm processes, and result in safe and quality food and non-food agricultural products" (Anonymous 2003). During 1997, to set standards for the certification of agricultural products around the globe, Euro-Retailer Produce Working Group (EUREPGAP) were initiated, which later evolved into GLOBALGAP. The four pillars of GAP are economic viability, environmental sustainability, social acceptability and food quality and safety. There are 14 major principles of GAP which include traceability, record keeping and self-inspection, varieties and rootstocks, site history and site management, soil and substrate management, fertilizer use, irrigation/fertigation, crop protection, harvesting, produce handling, waste and pollution management, recycling and re-use, worker health, safety and welfare, environment issues and complaint form.

Greenhouse production systems require adherence to GAP protocols because exhaustive cultivation in greenhouses often involves excessive use of chemicals since the stakes are high due to intensive inputs and high expectations on quality front. The food chain of fresh fruits and vegetables being a complex issue due to its perishable nature, the implementation of GAP becomes crucial (Nichols 2007). The perennial production coupled with indiscriminate chemicalization often leads to high levels of pesticide residues. Pest situations are often more severe in older greenhouses and hence maintaining economic profitability of farms is difficult as pest multiplication is much faster– compelling growers to resort to excessive chemical use, thereby requiring even stricter adherence to GAP protocols (Sabir *et al*. 2010).

Grafting in vegetable crops

Grafting of vegetable seedlings is a unique horticultural technology to overcome soil-borne diseases and nematodes and to add extra vigour to the plants under various environmental stresses. It is a process involving, the choice of rootstock and scion species, creation of a graft union by physical manipulation, healing of the union and acclimation of the grafted plant (Lee and Oda 2003). Vegetable grafting is a recent innovation adapted on a commercial scale though grafting of fruit trees has been practised since thousands of years (Sakata *et al*. 2007). Commercial grafting originated in Japan and Korea and was introduced to western countries in early 1990s and is currently being practised globally. Grafting involves the use of proper rootstocks which helps in curtailing problems associated with successive cropping and stress tolerance (Lee *et al*. 2010, Lee 1994, Lee *et al*. 1998, Lee and Oda 2003). Since grafting gives increased disease tolerance and vigour to crops, it will be useful in the low-input sustainable horticulture of the future especially for the following advantages:

- Achieving resistance or tolerance to soil-borne diseases (Edelstein *et al*. 1999, Cohen *et al*. 2000, 2005, 2007, Morra and Bilotto 2006).
- Acquiring tolerance to abiotic stresses, e g to induce resistance against low and high temperatures (Venema *et al*. 2008), to enhance nutrient uptake (Colla *et al*. 2010), improve water-use efficiency (Rouphael *et al*. 2008), limit the negative effect of mineral toxicity (Edelstein *et al*. 2005, Savvas *et al*. 2009).
- Plant vigour promotion, e g for efficient nutrients and water absorbing root systems of the selected rootstocks or the scion capable of converting the composition of cytokinins in the ascending xylem sap and higher cytokinin concentration in the ascending xylem sap contributes to growth promotion (Lee *et al*. 2010).
- Increase of yield – e g tomato with up to 54% increase in marketable yield as in 'Kagemusia' and 51% with 'Helper' rootstocks (Chung and Lee 2007). Similar increase in yield of cucumber (Lee and Oda 2003), pepper, eggplant and melons were reported.

Since 1987, mechanized grafting operations have been attempted to reduce the labour input required, as grafting is extremely laborious and time-consuming. In 1993, the first commercial robot for grafting cucumber seedlings was developed (Kobayashi 2005). By combining the adhesive and grafting plates, semi and fully automated grafting robots for plugs have also been developed (Kurata 1994, Oda 1995) resulting in manifold faster grafting.

Crop	Grafting method used
Cucumber	Tongue approach, splice
Watermelon	Hole insertion, tongue approach
Tomato	Pin grafting, tongue approach
Eggplant	Cleft, pin grafting
Pepper	Splice

Source: Lee and Oda 2003

Greenhouse tomato

Tomato is the most universally grown greenhouse vegetable crop found in varied agro-climatic regions all over the globe and is used as a salad, vegetable, fruit and in canning processes. Tomato varieties (cluster, heirloom, cherry etc) grown under greenhouse conditions are of indeterminate type as they continue to grow and set fruits almost for a year-long plant life (Atherton and Harris 1986). Apart from the newer and high-yielding hybrids, latest technique gaining popularity in greenhouse tomato cultivation around the world is the grafting technology that not only decreases susceptibility to root diseases, tolerance to soil salinity but also increases fruit production through increased plant vigour (*http://www.hort.uconn.edu/ipm/greenhs/htms/Tomgraft.htm*). Tomato harvesting is a continual process which lasts throughout its growing season. Large sized fruits are harvested singly with their calyx attached, while some smaller varieties are harvested in bunches.

Greenhouse lettuce

Lettuce is grown almost exclusively for the fresh market for salads, sandwiches and as a garnish. Its production in greenhouses has become popular and potentially a profitable venture. Greenhouse lettuce is grown primarily in soilless media, using rookwool, perlite or a hydroponic nutrient film technique (NFT) (Elmhirst 2006, Morgan and Tan 1983). Hydroponic lettuce is produced either through nutrient film technique (NFT) or the floating raft method, both as closed systems (*http://www.uky.edu/Ag/NewCrops/introsheets/hydrolettuce.pdf*). The major advantages of hydroponic lettuce include a short production period (35-40 days), availability year round, and consistency of product attributes. Production of greenhouse lettuce requires strict control of temperature, light, carbon dioxide concentration and relative humidity (RH).The major diseases encountered in hydroponics are *Pythium, Phytophthora, Botrytis* gray mold, powdery mildew and downy mildew; while pests of particular concern are aphids, thrips, whiteflies, and mites.

Greenhouse pepper

Greenhouse capsicum production is a lucrative industry in itself though it is more laborious than growing tomatoes. Despite the fact that it is a valuable crop with excellent prospects, it is slow growing, needs a high temperature to develop, fruit set occurs in periods and fruits are harvested in flushes (*http://www.hortnet.co.nz/publications/hortfacts/hf359001.htm*). Different coloured varieties of capsicum, viz. red, yellow, green and black are high in demand at fast food restaurants for variety of food preparations, extraction of natural colours and preparing oleoresins and oils (*http://www.unlimitedprojects.com/a21.html*). They may also be used for producing paprika which is used for colouring foods, flavouring and in sauces (Burt 2005). The coloured varieties rich in Vitamin A, Vitamin C and antioxidants along with processed products have very well added to the market value of capsicum and fetch a premium price in the international market.

Proper growth of capsicum is much dependent on temperature, particularly the root temperature (20-22°C) along with high humidity (80%). From the main stem, after 9-13 leaves, the capsicum plant naturally develops two shoots which will continue producing a terminal flower and two side shoots at every internode. It is mainly a self-pollinating crop but electric pollinator and bumblebees are also used for pollination. The fruit setting depends on optimum light, low temperature and increased CO_2 concentration. High fruit load might be a burden on roots which may cause decay and entry point for pathogens. Removal of excess fruits ensures improved fruit quality and fruit size. The major damage caused to capsicum is through thrips, mites and fungal diseases like *Pythium/Rhizoctonia, Botrytis,* powdery mildew, *Fusarium* wilt and *Cercospora* leaf spot.

Greenhouse cucumber

Cucumbers are popular greenhouse vegetable crops grown throughout the world. It grows best under condition of high light, humidity, moisture, temperature and fertilizer, being a warm season vegetable. Seedlings are raised in nursery in protrays, with a single seed per well ensuring minimal root damage while transplanting. Seedlings are ready for transplanting in 2-3 weeks after sowing. Being a vine crop, they are grown with a trellis system. The plants are trained upwards and trellising of the plants is done carefully to avoid any damage to the flower buds. Parthenocarpic cucumber cultivation in greenhouse can be a profitable venture for the vegetable growers and yearly three crops can be taken (Singh and Kumar 2006). They produce earlier and more fruits/plant compared to tomatoes and capsicum. Greenhouse cucumbers are tender skinned and prone to water loss and tend to desiccate and bruise faster, hence to extend their shelf-life, the harvested fruits are shrink-wrapped which is a labour-intensive process. The greenhouse cucumber cultivation by adoption of hydroponics (Brentlinger 2007) and grafting technology (Uysal *et al*. 2012, Lee 1989, Wittwer and Honma 1979) can not only aid in increased production but also to alleviate pest and diseases to a large extent and facilitate development of competent varieties. Soilless cultivation of greenhouse cucumber yields more compared to the conventional soil-based cultivation (Engindeniz and Gül 2009). In soilless system, there is an increased efficiency in the use of fertilizer and water which can be recycled and the returns from the greenhouse production of cucumbers exceed that from field production (Cantliffe *et al*. 2008). Biotic stresses particularly those caused by soil-borne pathogens and sucking pests of greenhouse cucumber can be effectively managed by adopting IPM methods where biorationals and bioagents play a crucial role (Sabir *et al*. 2011, Deka *et al*. 2011, Jayaraman *et al*. 2011, Bradley and Punja 2010).

Under Indian conditions successful cultivation of greenhouse cucumber through healthy production practices including GAP and IPM have given yields up to 50 q/1 000 m^2 area in a span of four months and very high profitability for small growers (Singh and Sabir 2012 *http://www.iari.res.in/files/Success_Story-Parthenocarpic-Cucumber-11062012.pdf*). Similarly, greenhouse capsicums yield about 8 tonnes/1 000 sq. feet area and fetch around ₹ 4-5 lakh per acre (*http://www.tribuneindia.com/2011/20110304/punjab.htm#9; http://www.thaindian.com/newsportal/india-news/tamil-nadu-capsicum-growing-farmers-reap-huge-profits_100175726.html*) while greenhouse tomatoes yield around 25 tonnes/quarter acre of land (http://www.thaindian.com/newsportal/india-news/coimbatore-farmer-gets-high-yield-of-tomatoes-using-green-house-technology_100277745.html).

Other vegetables

Similar success stories of growing tomato, capsicum, chillies, long gourd and seedless cucumber in Nabha, Punjab, India and gave yields of about ₹ 4-5 lakh per acre from capsicums (*http://www.tribuneindia.com/2011/20110304/punjab.htm#9*) and 25 tonnes from one fourth of acre in Coimbatore as against similar yields from one acre. (*http://www.thaindian.com/newsportal/india-news/coimbatore-farmer-gets-high-yield-of-tomatoes-using-green-house-technology_100277745.html* and *http://www.thaindian.com/newsportal/india-news/tamil-nadu-capsicum-growing-farmers-reap-huge-profits_100175726.html*).

Pollination management

Pollination of flowers is very important and is needed for optimal fruit set and production of quality greenhouse vegetables. In greenhouses it can be achieved manually, mechanically (electric vibrators and air blowers) or through use of bumblebees, depending upon crop. It is assumed that electric vibrators or 'mechanical bee' are more effective, less time consuming and economical compared to air blowers and also produce greater marketable yield (Hanna 2004,

Pest scenario under protected environment

Pests	Common name	Scientific name	Host
Aphids	Melon aphid	*Aphis gossypii*	Tomato, capsicum, cucumber, lettuce
	Green peach aphid	*Myzus persicae*	Capsicum, tomato, lettuce
	Potato aphid	*Macrosiphum euphorbiae*	Lettuce, tomato
	Foxglove aphid	*Aulacorthum solani*	Capsicum, tomato
		Acyrthosiphon lactucae	Lettuce
Caterpillars	Cotton bollworm	*Helicoverpa armigera*	Capsicum, tomato,
	Asian cotton leafworm or tobacco cutworm	*Spodoptera litura*	tomato, capsicum, cucumber
	Cabbage looper	*Trichopulsia ni*	Lettuce
Leaf-miner	American serpentine leafminer	*Liriomyza trifolii*	Tomato, cucumber,
Mites	Broad or yellow mite	*Polyphagotarsonemus latus*	Capsicum
	Carmine spider mite	*Tetranychus cinnabarinus*	Tomato
	Vegetable mite	*Tetranychus neocalidonicus*	Cucumber
	Spider mite	*Tetranychus urticae*	Tomato, capsicum, cucumber,
Thrips	Chilli thrips	*Scritothrips dorsalis*	
	Western flower thrips	*Frankliniella occidentalis*	Tomato
	Banded greenhouse thrips	*Hercinothrips femoralis*	Cucumber, tomato
	Melon thrips	*Thrips palmi*	Many vegetables
	onion thrips	*Thrips tabaci*	Many vegetables
Whiteflies	Sweetpotato whitefly	*Bemisia tabaci*	Capsicum, lettuce
	Silverleaf whitefly	*Bemisia argentifolii*	Tomato, lettuce
	Greenhouse whitefly	*Trialeurodes vaporariorum*	Tomato, cucumber, capsicum, beans, lettuce
Powdery mildew		*Erysiphe cichoracearum, Podosphaera xanthii, Leveillula taurica*	Cucumber, lettuce, capsicum
Gray mould		*Botrytis lactucae*	Lettuce
		Botrytis cineria	Tomato,
Fusarium wilt		*Fusarium oxysporum f. sp. lycopersici*	Tomato
		Fusarium oxysporum f. sp. cucumerinum	Cucumber
Fusarium crown and root rot		*Fusarium oxysporum f. sp. radicis lycopersici*	Tomato
Damping off/ root rot		*Pythium ultimum, Pythium aphanidermatum*	Cucumber, lettuce
		Phytophthora spp., Rhizoctonia solani	Capsicum
Downy mildew		*Pseudoperenospora cubensis*	Cucumber
		Bremia lactucae	Lettuce
Root knot nematode		*Meloidogyne incognita*	Tomato, Capsicum Cucumber

http://www.entomology.umn.edu/cues/inter/inmine/Thripc.html; http://dsp-psd.pwgsc.gc.ca/collection_2009/agr/A118-10-19-2006E.pdf.

Major pests given above in table are soil-borne pathogens and sucking arthropod pests

Cuellar *et al*. 2001). But the mechanism of pollination with bumblebees is an effective alternative and has surpassed all other methods (Banda and Paxton 1991, Dogterom *et al*. 1998). They are more effective pollinators of greenhouse crops like tomato, cucumber, capsicum etc. Different species used in greenhouses are *Bombus terrestris*, *B. impatience* and *B. occidentalis*. Stingless bees (*Scaptotrigona depilis* and *Nannotrigona testaceicornis*) can also be successfully used as pollinators of greenhouse cucumbers (Santos *et al.* 2008). The dipteran species *Eristalis tenax* possesses desirable attributes for the pollination of *Capsicum annuum* under greenhouse conditions (Jarlan *et al.* 1997)

Key pests

Greenhouse vegetable crops grown the world over are vulnerable to various diseases and pest attacks as the environment inside is conducive for their rapid multiplication. The losses caused due to pests in greenhouses are tremendous. Crop losses are mainly due to arthropod pests like mites, whiteflies, thrips, aphids and diseases caused by virus, fungi, bacteria, nematodes etc. The amount of losses due to virus can vary from 5% to 90% depending on number of factors such as the strain of virus, the crop variety, age of the plant at infection time and temperature during disease development (Averre and Gooding 2004). Severe losses due to tomato mosaic virus (ToMV) had been reported in susceptible cultivars of pepper (Brunt 1986). Tomato infectious chlorosis virus (TICV) infects a wide range of plant hosts and a loss to the tune of $2 million has been reported from Orange County during 1993 to the world's tomato industry (http://californiaagriculture.ucanr.org/landingpage.cfm?article=ca.v051n02p24&fulltext=yes). In Mediterranean areas, crop loss went up to 100% due to whitefly transmitted tomato yellow leaf curl virus and in UK glasshouses western flower thrips caused 90% crop loss (Ferguson and Murphy 2002). Some significant crop losses are reported on greenhouse vegetable crops due to *Pythium* species (http://www.agf.gov.bc.ca/cropprot/pythium.htm). *Botrytis* spp may cause severe post-harvest losses in plant products during storage or transportation (Trolinger and Stider 1985).

IPM and safe vegetable cultivation

Of late the occurrence of resistance to chemical pesticides in managing greenhouse pests and also the demand for less usage of pesticides with the consumers requiring residue-free food, paved the way for the use of biological management which in-turn helped in formulating integrated pest management (IPM) measures for sustainable crop protection (Albajes *et al*. 1999, Van Lenteren 2000). The strategy of IPM prevents pest damage with minimal adverse impact on human health, non-target organisms and the environment. It involves the integration of all suitable plant protection measures so as to restrict the pests below economic threshold levels keeping in view the profitability of the farmer, health of the consumer and sustainability of the environment. Insects and diseases being a major challenge to greenhouse production, managing them is of utmost importance to produce healthy, pest and damage-free plants. Hence a greenhouse IPM programme should involve a bio-intensive approach including sanitation, mechanical barriers, scouting, GAP protocols, biocontrol and selected pesticides whenever necessary. Presently, throughout the globe, IPM is being followed for almost all greenhouse vegetable crops like tomato, cucumber, sweet pepper, brinjal, lettuce etc. (Van Lenteren and Woets 1988, Albajes *et al*. 1999, Sabir *et al*. 2011).

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