Diagnosis and Management of Biotic and Abiotic Stresses of Vegetable Crops in Protected Agriculture and Natural Farming

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Ajay Kumar Sood, Amar Singh, Ranbir Singh Rana
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Sanjeev Kumar Sandal and Ruchi Sood**ISBN No.:978-93-5906-015-6**

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CAAST, NAHEP, ICAR-ON PROTECTED CUTIVATION AND NATURAL FARMING CSK HPKV, PALAMPUR

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Preface

Protected Agriculture (PA) is a concept of growing potential crops in modified natural environment for ensuring optimum growth of the crop plants without any or least stress. In India, with the concerted efforts of different farm universities, ICAR and developmental agencies for the last two decades, an area of over two lakh hectare has been brought under protected cultivation of high value crops from coastal and tropical plains to the temperate regions of the country. In Himachal Pradesh, potential vegetable and ornamental crops are grown in Protected Agriculture which ensures their better productivity and quality. PA also provides congenial environment for insects, mites and nematode pests and diseases. Many a times, signs and symptoms produced by abiotic stresses, eg. high temperature and nutritional disorders etc. resemble to those caused by insect-pests and pathogens. The complexity of biotic and abiotic stresses and the high cosmetic standards of produce compel the growers for excessive and injudicious use of agrochemicals. This results in increased production costs, residual toxicity and adverse effects on the health of the applicators and consumers alongwith environment, soil and water pollution. It leads to management of plant stresses more challenging especially under PA. Therefore, accurate diagnosis of the biotic and abiotic maladies and their management with emphasis on safe products of organic and natural origin, biological control agents and plant extracts has become a compelling necessity. The PA is becoming popular among all the strata of the farmers especially under hill ecology which is highly congenial for the early season nursery raising, cultivation of off season high value cash vegetable crops like capsicum, cucumber, tomato etc. Moreover, the PA has enabled to produce tropical vegetables in snow bound areas like Leh and Ladhak.

Keeping this in view, training-cum-webinars were organized on 'Diagnosis and Management of Biotic and Abiotic Stresses in important Vegetable Crops' being grown under Protected Agriculture during September 2021 and March & April 2022. These were held under the auspices of 'ICAR-NAHEP Centre for Advanced Agricultural Science and Technology (CAAST)' on Protected Agriculture and Natural Farming operational at CSKHPKV, Palampur. The main aim was to upscale the capacity of the postgraduate students, faculty, researchers, extension personnel of SAUs and ICAR Institutes in developing and disseminating the technologies for biotic and abiotic stress management under PANF cropping systems. The training was conducted in online and offline hybrid mode. In all 150 participants from 13 states covering 23 SAUs and ICAR institutes participated in the training. Fifty three candidate's attended the training in off line mode. There were 20 experts who shared their knowledge to further augment the quality of research in the thematic area.

The book entitled, "Diagnosis and Management of Biotic and Abiotic Stresses in important Vegetable Crops in Protected Agriculture and Natural Farming" comprises 23 chapters featuring the concepts and applications of plant protection under protected agriculture with special emphasis on eco-friendly disease and insect pest management options with theoretical and practical approaches as well as plant nutrient and water stress, diagnosis and management under protected cultivation.

This book is expected to be of great significance to the students, extension workers and of course to the teachers and researchers engaged in PANF. It will also offer a reference guide for policy makers and practicing farmers especially those interested in organic agriculture and natural farming.

It is our immense pleasure to express deep sense of gratitude and sincere thanks to Professor H.K. Chaudhary, Hon'ble Vice Chancellor CSKHPKV, Palampur, and Dr. R.C. Aggrawal

Hon'ble Deputy Director General (Education), ICAR, our patrons, for their persistent, consistent, sustainable leadership, kind support, guidance and constant encouragement. Our heart felt thanks are due to Dr. (Mrs.) Anuradha Agarwal for her keen interest, active cooperation and ever willing help in successful conduct and completion of the trainings. Cooperation received from Deans and Directors of the university is sincerely acknowledged. The successful conduct and compilation of the webinars is due to timely delivery of the lectures by the able experts and submission of text which could be transformed in the form of present book for the benefit of stakeholders. The project staff especially Ms Ekta Kaushik, Diksha Sinha (JRFs), Anjali Dhiman, Somya Hallan, Sachin Kaushal and Er. Shakiv Pandit made tireless efforts to make the training cum webinars a great success. Their contribution is gratefully acknowledged. The help rendered by all convenors, co-convenors and members of various committees is deeply acknowledged for their efforts in successful execution of various training related activities.

The financial help rendered by ICAR through World bank funded project `Centre for Advanced Agricultural Science and Technology (CAAST) on Protected Agriculture and Natural Farming (PANF)`under ICAR-NAHEP at CSKHPKV, Palampur is gratefully acknowledged.

Editors

Vice- Chancellor
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Foreword

In protected agriculture, high value crops are grown under modified natural environment to combat the abiotic and biotic stresses to enhance their quality and production. The Indian Council of Agricultural Research, SAUs and various public and private developmental agencies are making persistent and continuous efforts for the last more than 20 years to popularize this venture. It has yielded remarkable progress and an area of over two lakh hectares has been brought under protected cultivation of high value crops in the country. The cultivation of such high value crops under poly houses have emerged as an attractive and remunerative entrepreneur among the young farmers especially under hill ecology for early season nursery raising. The technology has been standardized to grow the tropical vegetables now in snow bound areas like Leh, Ladakh, Lahaul & Spiti and Kinnaur. In Himachal Pradesh, several vegetable crops like capsicum, cucumber, tomato and ornamental crops are grown under protected conditions which ensure their higher productivity and quality. Protected environment provides optimal environment for crop growth but reduces biotic and abiotic stresses. The farmers resort to excessive and injudicious use of agro-chemicals to increase the cosmetic value of their produce. Certainly, it enhances the input costs and leads to adverse effects on the health of growers, consumers, non-target organisms and environment, development of resistance in the target pests against the pesticides and residual toxicity. The management of biotic and abiotic stresses using eco-friendly techniques becomes more challenging especially under protected agriculture. The CSKHPKV, Palampur organized a series of training and webinars to up scale the knowledge of stake holders i.e. post graduate students, extension personnel and researchers, on diagnosis and management of biotic and abiotic stresses in vegetable crops under NAHEP on Protected Agriculture and Natural Farming and it is highly commendable. Further, the scientists and the entire CAAST team have compiled the lectures delivered by the experts during these trainings and webinars in the form of book entitled, "Diagnosis and Management of Biotic and Abiotic Stresses of Vegetable Crops in Protected Agriculture and Natural Farming." The entire team lead by Dr. R S Rana deserves special appreciation for bringing out such an important publication, which is the necessity of the time. I take this opportunity to thank the ICAR and DDG, Education cum National Director NAHEP, Dr. R.C. Agrawal for his incessant moral and financial support for this activity.

This book will be of great significance to the students, extension workers as well as to the teachers and researchers engaged in Protected Agriculture and Natural Farming. It will also serve as a reference guide for policy makers and practicing farmers especially those interested in organic agriculture and natural farming.

Prof. HK Choudhary

Academic excellence in Agricultural Higher Education system in India is the need of the day. It may be attained by enhancing professional competence of faculty and to create world class infrastructure and lab facilities for the Post graduate students of the State Agricultural Universities. ICAR has embarked upon an ambitious step to fulfil this objective by launching ICAR, National Agricultural Higher Education Project (NAHEP) jointly with the support form World Bank and Govt. of India. Under this prestigious project, the CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur was sanctioned the Centre for Advanced Agricultural Science and Technology (CAAST) on Protected Agriculture and Natural Farming during 2019-20 with financial outlay of 1891.05 lacs. The university is indebted to ICAR for this. The project has been instrumental in augmenting the institutional capacity for globally competitive professionals in protected agriculture and natural farming. It has strengthened the higher agricultural education system (post-graduation) to enhance the quality of human resources, equipped with skill and entrepreneurship in PANF to meet future challenges and the university has become the knowledge leader on it. The project has also the mandate to study the new endeavours pertaining to theme and improvement in teaching and learning process. The project will further help to strengthen linkage between the university and international research institutes, ensuing greater possibility for the students to take up entrepreneurship and generate employment.

The importance of Natural Farming is evidenced by its adoption by a large number of farmers in the country. It is heartening that in Himachal Pradesh, more women farmers have adopted Natural Farming. The practices of Natural farming have great mitigation potential of climate change also.

The present book entitled, "Diagnosis and Management of Biotic and Abiotic Stresses in important Vegetable Crops in Protected Agriculture and Natural Farming" has been compiled based on the lectures delivered by various experts during various trainings and national webinars on the theme area under the auspicious of ICAR-NAHEP-CAAST-PANF by the Department of Plant Pathology, Entomology and Soil Sciences. This book shall act as a text book for the students, farmers and extension workers of line departments and a guiding force for the policy makers.

I appreciate the efforts of Dr Ashwani Kumar Basandrai (Consulatant), Dr Ajay Sood and Dr. Amar Singh (CCPI, Crop Protection), Dr. NK Sankhyan and Dr S.K.Sandal (CCPI, Plant Nutrition), and the entire team for compiling this useful publication and congratulate them. I am highly indebted to Dr. HK Chaudhary Honorable Vice Chancellor for his kind support. On the behalf of CSKHPKV Palampur, my special gratitude is towards Dr RC Agrawal, DDG (Edu)-cum-National Director NAHEP ICAR and National Coordinator, Dr Anuradha Agrawal for their constant encouragement and monitoring of the project activities for its successful execution.

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Dr. Ranbir Singh Rana
Principal Investigator

1. DISEASE MANAGEMENT OF VEGETABLE CROPS UNDER PROTECTED CULTIVATION

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Abstract: Greenhouse agriculture i.e. Protected Agriculture has become a very popular technology for cultivating vegetables, flowers and others high valued as well as perishable crops. In smart agriculture, protected structures have an extreme potential for high production and higher productivity with better quality of produce than in the open field with higher gross and net returns. However, farmers face problems of low yield and poor-quality marketable produce due to various constraints i.e. diseases, insect-pests, nutrient deficiencies, lack of quality planting materials and management technology. The protected structures are costly, but may be compensated by adopting good production and protection technology of crops out of which crop protection is the major pillar of integrated crop management and among various biotic and abiotic stresses, diseases caused by fungi, bacteria, viruses, and nematodes take a heavy toll of the crop. Some of the minor diseases occurring under field condition, have become major under protected condition. Greenhouses are designed to protect crops from many adverse conditions, but most pathogens and several pests are impossible to exclude. Airborne spores and aerosols containing bacteria enter doorways and ventilators. Soilborne pathogens enter in the airborne dust particles and adhere to footwear and machinery, aquatic fungi can be dispersed through irrigation water. Insects entering the greenhouse can transmit viruses and can carry bacteria and fungi as well. Once inside a greenhouse, pathogens and pests are difficult to eradicate and need an urgent attention.

Introduction

Production of horticultural crops like vegetables, fruits and flowers are inflicted by biotic and abiotic stresses to a great extent in open conditions which can be avoided by effective utilization of protected cultivation system. This technology enables an increase in the production of quality fruits, vegetables, and flowers both for the export and domestic markets. It provides appropriate conditions for off-season cultivation of tomato, capsicum, cucurbitaceous crops, like tomato, cucumber etc. and have become popular with the farmers and gaining momentum in India. Changing climate which showed increase in maximum and minimum temperatures and on contrary decreasing trends of rainfall in Himachal Pradesh (Rana et al., 2012) may further expected to impact prevalence of diseases in Mountain Agriculture. However, there is problem of low yield and poor-quality of marketable produce under protected cultivation due to various constraints amongst which diseases play a major role.

Prevention of diseases in protected vegetable crops: Fungal diseases are the largest group of pathogens causing immense damage under protected environment. The incidence and severity of diseases vary considerably under protected agriculture when compared to the open field. The important fungal diseases viz. late blight, powdery/downy mildew, leaf mould, anthracnose, wilt, stem rot etc. cause severe losses in vegetable crops. Bacterial diseases can be extremely serious and destructive under PA. Plant pathogenic bacteria develop mostly in the host plant as parasites on plant surfaces, especially buds as epiphytes and partly in plant debris or in the soil as saprophytes. Some air-borne bacterial pathogens such as *Clavibacter michiganensis* sub sp. *michiganensis*, causing bacterial canker of tomato and *Pseudomonas syringae* pv. *lachrymans*, causing bacterial spot or angular leaf spot of cucurbits, infect and reproduce in the host plant whereas, bacterial plant pathogens such as *Ralstonia solanacearum* are soil-borne causing bacterial wilt of solanaceous crops. Soil-borne bacteria build up their populations within the host plants, but these populations decline gradually when released into the soil. Viral diseases cause severe damage resulting into huge losses in protected vegetable cultivation under PA the worldwide which varies depending on the virus strain, the host species and the age of the plant at the time of infection. Tomato, cucumber and capsicum are the major crops which are prone to the viral diseases under protected cultivation. Some important diseases viz. tomato mosaic virus, tomato leaf curl virus, tomato spotted wilt virus and cucumber mosaic virus cause severe diseases under protected environment. More than 80% of the plant viruses can be transmitted by insects i.e. primarily by aphids, leafhoppers, thrips and whiteflies, and secondarily by mites, fungi and nematodes. Viruses usually begin infection through a wound, mostly through insect feeding. Once a plant is infected, the virus spreads systemically within the plant. Viruses are often spread by propagation of infected plant parts (cuttings, bulbs, and sometimes seeds), and by mechanical means including contact (rubbing, abrasion, or by handling).

Diseases of Tomato and their integrated management

Cultural Control:

Late blight: Use certified and healthy seeds, produced in disease free area. Seeds should be treated with Thiram @ 2-3 g/kg of seed before transplanting. Mulching in polyhouses reduces the disease severity as the soil surface and soil temperatures remain warmer.

Leaf mould: The protected structures should be kept warmer than the outside at night. It should be well ventilated if the humidity is >85%. Crop residue should be removed and destroyed after the crop harvest to reduce the inoculum.

Bacterial canker: Bacterial canker is difficult to eradicate once it is established in a polyhouse hence, its introduction, establishment and spread should be prevented in a greenhouse. Follow strict overall sanitation and biosecurity procedures. Disease free seed/transplants may be purchased from a reliable source and it should be treated. Seed derived from an "acid extraction" procedure is highly recommended. Use resistant cultivars. Diseased plants should be removed along with surrounding healthy plants by cutting off at the ground line. Sanitation i.e. disinfection of hands, shoes, tools, and crop-supporting wires should be practiced. All infected crop debris and fruits must be collected from the polyhouse and burnt.

Tomato mosaic virus (ToMV): Eradicate perennial and biennials from surrounding areas. Seed should be treated by dry heating at 70°C for 4 days or at 82-85°C for 24h to eliminate surface-borne virus. Seed coat infection can be eliminated by soaking the seed in 100g/l solution of tri-sodium phosphate (TSP) for 15 min, followed by rinsing it thoroughly and then drying. Use TMV-resistant tomato varieties. Avoid planting of the susceptible crops such as tobacco, pepper, eggplant, or cucurbits. Make sure transplants are healthy and certified as disease free. Use steam-pasteurized soil for transplants in polyhouse. Avoid touching or handling plants prior to transplanting. Discard diseased seedlings showing leaf twisting, mosaic, or unusual growth and avoid touching other seedlings while discarding them. Remove diseased plants as soon as virus symptoms are noticed. Disinfect tools, stakes, and equipment after their use in diseased areas by:

(1) Heating or steaming at 150°C for 30 minutes;

(2) Soaking for 10 minutes in 1% formaldehyde or a 1:10 dilution of 5.25% sodium hypochlorite

(3) Washing in a detergent. Discourage smoking by workers and encourage the practice of washing hands with soap and water before and after handling the plants using fresh solutions .

(4) Tools should be always be washed thoroughly by dipping in 3% (w/v) TSP for 30 minutes before and after use.

(5) Hands should be washed and scrubbed well with 3% TSP followed by thoroughly rinsing with water.

Tomato yellow leaf curl virus (TYLCV): Clean up polyhouse immediately after final crop harvest.

Tomato spotted wilt virus (TSWV): Remove and destroy infected plants showing any symptom initiation to reduce virus spread. Use blue or yellow sticky cards to attract thrips for monitoring their populations. Avoid sequential planting because thrips can continue to emerge from the soil for 2–3 weeks from crop residues.

Biological control

Seed treatment with bioagents is a viable option. Green manuring followed by application of *Trichoderma* formulation @ 5 kg/ha within a week of bed preparation. Neemcake is ground into powder, moistened and kept for two days followed by its mixing with *Trichoderma* formulation @ 1kg/100 Kg neemcake. The mixture is covered with a plastic sheet and it is turned at two days interval and applied after 15 days in sanitized beds @200g/square m and mix it thoroughly.

Chemical control

Late blight of tomato: Spray Copper hydroxy chloride 50% WP @ 3g/liter or Metalaxyl MZ 72% WP @ 2g/liter or Mancozeb 75% WP @ 2g/liter of water. It is better to avoid capsicum cultivation in severely affected structures.

Leaf mold of tomato: Spray Chlorothalonil 75% WP or Mancozeb 75% WP or Copper hydroxide 53.6% WP @ 2g/liter water or apply preventive fungicides eg. Thiophanate-methyl 70% WP @ 1g/liter, Triflumizole 50%WS and Chlorothalonil 75%WP (TPN) in combination with cultural methods explained above.

Bacterial canker of tomato: Antibiotic Kasugamycin 3% SL @ 1.25ml/liter and/ or fungicide Copper oxychloride 50% WP @ 3g/liter sprays help in protecting healthy plants, especially in case of external symptoms.

Tomato yellow leaf curl virus (TYLCV): Imidacloprid 17.8% SL @ 250ml/ha or Thiamethoxam 25% WG @ 200g/ha should be used for control of insect vectors/ disease.

Tomato Spotted Wilt Virus (TSWV): Soil fumigation with metham sodium (Vapam) or 1, 3-dichloro-propene (Telone) is effective to eliminate thrips associated with crop debris. Control of insects (thrips) is important to reduce spread of the virus by vectors using systemic insecticides viz. Imidacloprid 17.8% SL @ 250ml/ha or Thiamethoxam 25%WG @ 200g/ha. Apply insecticides on the weeds bordering the tomato crop to suppress thrips populations and the spread of TSWV.

Bacterial wilt

Cultural practices: The bacterial cells are released into the soil from the decaying roots and stems after the death of plants hence, infected roots should be removed immediately. Soil fumigation, using chloropicrin is effective to a great extent under protected conditions. Sanitation should be practiced to prevent secondary infection by using and keeping the tools clean.

Bacterium can survive for long periods in the soil hence, crop rotation, excluding solanaceous crops should be followed for three years as even in the absence of host plants bacteria can survive for long period. Keep soil well drained.

Biological control: Several biological control agents eg. *Pseudomonas fluorescens* (10g/m^2), *Bacillus licheniformis, B. cereus, B. subtilis* and mycorrhiza are effective in delaying and reducing the wilt development.

Chemical control: Drenching the fields with Kasugamycin 3%SL @ 1.25ml/litre, copper oxychloride 50% WP @3g/litre, bleaching powder @300g/200m^2; Streptocycline (0.1 g/liter of water)+Copper oxychloride (3 g/liter of water) are effective. Application of bleaching powder @ 15kg/ha has been found very effective. Seedling dip in streptocycline in 40-100ppm solution avoids early invasion and infection through wounds during transplanting. Streptomycin sulphate 9% SP or oxytetracycline sprayed @ 200ppm at 7 days interval were effective.

Diseases of cucurbits and their integrated management

Downy mildew of cucurbits

Cultural practices: All parts of infected plants should be removed and discarded. Weeds of the family cucurbitaceae eg.,*Trichosanthes cucumeroides* surrounding the protected structures should be removed which may serve as reservoirs of the fungus.

Growing cucurbits in environments with low humidity levels can help to manage downy mildew eg., trellising in cucurbits, increasing plant or row spacing or growing in passive or traditional greenhouses can help to reduce relative humidity and leaf wetness. Dew formation should be avoided through adequate heating and ventilation in protected facilities. Mulching in greenhouses reduces the disease severity as less moisture is supplied from the soil surface.
Biological control: *Bacillus subtilis* @ 10 g/liter of water is effective for the management of downy mildew in vegetable.
Chemical control: Normal Suitable and judicious control procedures must be implemented in the early stages of disease development i.e. with the appearance of disease. The spores are readily dispersed by air currents under favourable conditions and disease develops rapidly. Registered fungicides i.e., Cymoxanil 8% + Mancozeb 64% WP @ 2g/liter water or or Azoxystrobin 23% SC @ 0.5ml/liter of water should be sprayed .

Powdery mildew of cucurbits:
Biological control: *Use of Ampelomyces quisqualis* is effective.
Chemical control: Spray carbendazim /benomyl/ propiconazole/difenconazole/hexaconazole @0.1% has been recommended. Cucurbits are sensitive to Sulphur dust

Bacterial spot/Angular leaf spot
Cultural practices: Use of pathogen-free seeds. Follow crop-rotation for at least 2 years with non-cucurbitatious crops. Avoid overhead watering, sprinkler irrigation etc.
Biological control: Use the biological formulations i.e. *Pseudomonas fluorescence* or *Trichoderma* spp. for soil and seed treatment.
Chemical control: Spray of copper oxychloride 50WP @ 3g/liter or Streptomycin sulphate 9%SP + Tetracycline hydrochloride *1% SP* (Agrimycin) @ 6g/litre at younger stage of the crop growth (do not use during fruiting stage) or Copper hydroxide 77% WP @ 2g/litre or Cuprous oxide 4% DP @ 2g/litre can be applied with the initiation of the disease.

Anthracnose of cucurbits
Cultural practices: Crop rotation, host destruction, seed treatment with hot water at 57.2°C for 20 minutes are the recommended practices.
Chemical control: Seed treatment with Carbendazim @ 2g/kg of seeds, followed by its foliar spray @1.25g/ litre or Mancozeb @0.2% with the initiation of the disease.

Cucumber mosaic virus (CMV)
Cultural practices: CMV can overwinter in perennial plants and weeds. The virus enters the roots and remain at the top of the plant during the spring time where it can be retransmitted by aphids. Eradicate all biennial and perennial weeds and wild reservoir hosts in and around polyhouses. Maintain a distance of at least 10 yards between susceptible crops and the weeds or other susceptible plants.

Grow seedlings in a structure or seedbeds protected with mesh net $\geq$32 to prevent entry of aphids. Discard seedlings or young plants showing virus symptoms and while handling the infected ones do not touch other healthy seedlings. Avoid touching or handling plants prior to transplanting and dip hands in milk while handling plants.

Do not clip or damage young seedlings to avoid possibility of mechanical transmission of the virus from contaminated tools or hands. Remove diseased plants from the field with the initiation of symptoms which will reduce the spread of the virus by aphid vectors. Use resistant varieties.
Chemical control: Spray of neem seed kernel extract (2%) is highly effective and must be used in rotation with insecticides i.e. imidacloprid 17.8SL @ 1ml/liter of water for control of sucking insects.

Gray mold of vegetables

Cultural Practices: Adequate spacing between plants and proper weed management is recommended for good air circulation. Excessive humidity and formation of water film on foliage may be avoided. Maintain higher greenhouse temperature than outdoor to prevent condensation of water on leaves

Chemical Control: Spray the crop with fungicides i.e. Chlorothalonil 75% WP/ Mancozeb 75% WP/ Iprodione 50% WP @ 2g/liter or Difenoconazole 25% WP @ 0.5ml/liter or Azoxystrobin 23% SC @ 0.5ml/liter or Diethofencarb- thiophanate-methyl 65% WP @ 0.5ml/liter at 5-7 days intervals. The fungus produces resistant strains against the chemicals hence, fungicides should be sprayed in alteration.

Powdery mildew

Cultural Practices: Disease prefers dry conditions for its development but germination of conidia requires moisture. Good air circulation is effective to prevent infection. Avoid excessive use of nitrogen.

Biological Control: *Bacillus subtilis* @ 10 g/liter of water has been reported to be effective for management of powdery mildew in vegetables.

Chemical Control: Wettable sulfur 80%WP @ 2-3g/liter or Azoxystrobin 23% SC / Hexaconazole 5EC @ 0.5ml/liter or Myclobutanil 10% WP/ Pyraclostrobin 20% WG @ 1g/liter/ Tebuconazole 25.9% EC @ 1ml/liter is effective. Integration of cultural and chemical methods is practically important in susceptible cultivars.

Sclerotinia rot of vegetables

Cultural Practices: Collect and destroy the infected plant material, to prevent formation of sclerotia in contaminating the soil. Soil should be removed at the base of severely affected plants and discarded in the garbage (i.e. it should not be composted) to eliminate fallen sclerotia. Several weeds are hosts for this fungus hence, practise good weed control. Avoid wetting the foliage, and susceptible varieties should be planted only in well- drained soils.

Chemical Control: Chemical treatments are recommended in severe disease incidences. Registered chemicals i.e. Thiophanate- methyl 70% WP, Iprodione 50%WP and Captan 75% WP are highly effective to management of the disease.

Conclusion

Greenhouse/Protected Agriculture is the most intensive form of crop production practice with higher investment and labour costs however, with high yield and quality produce. The seasonal vegetable crops can be produced in protected cultivation for higher crop productivity and better quality of produce throughout the year thus leading to more profit as it can increase five folds production per unit of land, water, energy, and labour. Vegetable crops are adversely affected by several diseases caused by fungi, bacteria, viruses etc. under protected environment therefore, it is a major challenge to greenhouse production. The warm and humid climatic conditions are the most congenial for the development of several foliar and soil borne plant diseases. Integration of cultural, physical, biological, and chemical control options are required for protection of crops from disease outbreaks within the soil and aerial environment under protected agriculture. The study conducted in Himachal Pradesh also indicated that climate variability has a clear impact on crop productivity and increase in vulnerability in climate dependent agricultural system. (Rana et al., 2013). Disease- free seed/planting materials, production of costly vegetable transplants can be produced under protected structures continuously with judicious, timely and eco-friendly management practices.

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2. DIAGNOSIS OF FUNGAL AND OOMYCETE ON DISEASES OF MAJOR VEGETABLE CROPS UNDER PROTECTED CULTIVATION

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Abstract: Plant disease diagnosis is one of the most important pre-requisite aspects for effective plant disease management. Its success mainly depends on quick and accurate identification of diseases and their causal agents. Any lapse in proper identification of the disease, its causal agent may result into yield losses, enhanced cost of production and ultimately the less profitability leading to lack of confidence and interest among the farming community. Proper disease diagnosis is an inevitable and vital component of plant protection. Generally, plant pathologists start with visualization of the symptoms for the identification of a disease problem. Similar symptoms may be produced in response to different causal agents however, dependence on symptoms alone is often an inadequate method for disease identification. Identification of pathogen may take long time and requires the axenic culture of pathogen for accurate confirmation of the possible cause of problem. Besides this, information on various environmental and cultural factors is also required.

Introduction

Various steps are involved for the accurate plant disease diagnosis (Riley et al 2002) and information is required to analyze the disease problem under field and protected environment, and these steps are being discussed in the present chapter.

Knowledge of healthy plant

Identification of affected plants is the first step in plant disease diagnosis. The features and appearance of a healthy plant of a cultivar should be normal, as variation in susceptibility to a specific disease may occur within different cultivars of a plant species. Such information of cultivar and its susceptibility to various diseases may further narrow down the possibility of disease agents to be considered. Each plant species has special growth habit, colour and morphology on the basis of which comparison between diseased and healthy plant may be done easily.

Disease distribution pattern in field

Observe the disease distribution pattern among the plants in the field or polyhouse. Uniform pattern is often associated with some abiotic agents whereas, generally pathogenic diseases take more time to occur and their distribution is not uniform. The disease initiates at the point of infection and show progression of symptoms and its gradual spread, thus indicate the involvement of a biotic agent.

Information about cultural practices and weather conditions

This will help to rule out the problems related to activities carried out by the farmer and environmental factors. It is important to record changes in the environment and factors like site, shade, sunshine, soil type, drainage, and soil pH.

Identification of characteristic symptoms

Characteristic symptoms observed in diseased plant needs to be described accurately and compared on the basis of descriptions available in literature or in disease identification manuals or keys. It is important to record the affected plant part, as the symptoms of some diseases occur on specific plant parts and thus are important in the disease diagnosis. Generally, plant disease symptoms appear in following categories:

i) **Necrotic or death of plant parts:** Plants are generally attacked by several pathogens and develop the symptoms which appear as a result of cell and tissue death and manifest as leaf spots, leaf blights, blast, stem rot and fruit rots. Sometimes whole plant or major portion of the plant may be affected and exhibit symptoms such as wilt and dieback.

ii) **Restricted plant growth:** Some plant diseases reduce either cell division or their development or both which result in under growth of the plant tissues or organs hence, infected plant show symptoms such as stunted growth, shortened internodes, poor root development, reduction in chlorophyll and other pigments and malformation of foliage.

iii) **Over growth.** Disease causing agents can result in abnormal increase in cell division and/or their enlargement and infected plant exhibit symptoms i.e. tumour, knot, galls, witches' brooms, etc.

Diseases can produce primary and secondary symptoms. Generally secondary invaders may get associated in necrotic tissue resulting in changes in the typical disease symptoms, so disease identification becomes cumbersome and variations in symptoms expressed by diseased plants may result in improper diagnosis which may be due to prevalence of more than one problem, and/or more than one pathogens associated with infected plant.

Signs

Physical appearance of pathogen structures on the infected plant parts or organ is known as sign. Signs in fungal diseases may develop in the form of mycelium, spores and spore producing fruiting structures whereas, in bacterial diseases bacterial ooze, yellow halo etc. are the major signs. Signs are more specific to disease causing agents than the symptoms, hence are very useful in disease diagnosis. Powdery patches consisting of mycelia, conidiophores and conidia on plant surface are typically sings for diagnosing powdery mildew whereas, brown, yellow and black masses of either aeciospores, uredospores or teliospores exposed out from pustules are the typical signs for identification of rust diseases.

Microscopic examination

If, macroscopic examination of symptoms and signs do not help in disease diagnosis, microscopic analysis of disease samples is required to confirm the identification. Here, special characteristic features of pathogen structures such as spores, sporophores and fructifications are recorded which can lead to further identification of possible disease causal agent.

Laboratory examination

Sometimes, signs are not conspicuous or many secondary invaders may be involved with the infected plant parts, which makes the identification of actually associated agent difficult. In such instances, identification of pathogen is proceeded by placing the diseased samples in moist chamber or petri plate to induce sporulation of the pathogen after incubation and analyse these samples under microscope for identification. If case of saprophytic growth of secondary microorganism, establishing pure culture of the pathogen and proving its pathogenicity will help in confirming the actual pathogen.

Identification of non-culturable causal agents

The plant pathogens which are difficult or impossible to grow on artificial media, may be detected using diagnostic tests at molecular level viz. polymerase chain reaction (PCR), profiling of fatty acids, carbohydrate utilization and test for enzyme activity. Other sophisticated laboratory-based methods such as immunofluorescence (IF), fluorescence in-situ hybridization (FISH), enzyme-linked immunosorbent assay (ELISA), flow cytometry (FCM) and gas chromatography-mass spectrometry (GC-MS) are some commonly used methods for the direct detection of plant pathogens (Fang and Ramasamy, 2015). These require costly instruments, expensive chemicals and trained expertise. Some indirect methods viz. thermography, fluorescence imaging and hyperspectral techniques are also available.

The disease scenario on major vegetables under protected cultivation is presented in Table 2.1 and diagnostic feature of different disease is presented in Table 2.2.

Table 2.1 Scenario of plant diseases under protected cultivation in Himachal Pradesh

Crop	Disease	Severity	Occurrence
Capsicum	Powdery mildew	M-H	Widely distributed
	Root/collar rot	L-H	Sporadic
	Cercospora leaf spot	M-H	Widely distributed
	Grey mould	L-M	Severe in fogy area during Oct.-Feb.
	White rot	L	Sporadic
	Bacterial wilt	L-M	Sever under moderate temperature and high moisture
	Bacterial canker	L	-do-
	Pepper mild mottle virus	L-H	Widely prevalent
	Tomato spotted wilt virus	M	Sporadic
Tomato	Early blight	L	Wide spread
	Powdery mildew	L-H	Wide spread
	Gray leaf spot	M-H	Wide spread
	Septoria leaf spot	L	Sporadic
	Target spot	M-H	Wide spread
	Gray mould	L-H	Wide spread during September-February
	Late blight	L-M	Sporadic
	Bacterial wilt	M-H	Wide spread
	Fusarium wilt	L	Sporadic
	Damping off	L-H	Wide spread
Cucumber	Powdery mildew	L-H	Wide spread
	Downy mildew	L-H	Wide spread during rainy season
	Leaf spot	L-H	Sporadic
	Gummy stem canker	M	Sporadic

L=Low, M=Medium, H=High

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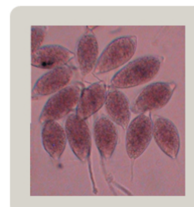
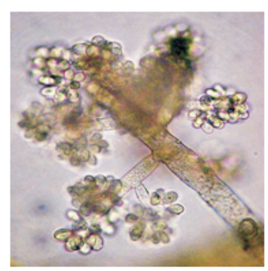
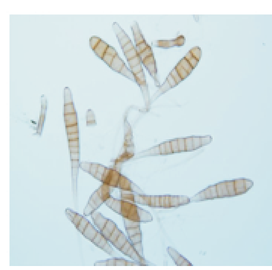
Table 2.2 Diagnostic features and causal organisms of some important diseases under protected condition

Disease	**Pathogen**	**Characteristic symptom of disease**	**Characteristic feature of pathogen**
Powdery mildew of capsicum	*Leveillula taurica*		
Root rot of capsicum	*Phytophthora capsici*		
Frogeye leaf spot of capsicum	*Cercospora capsici*		
Grey mould	*Botrytis cinearia*		
Early blight	*Alternaria solani*		

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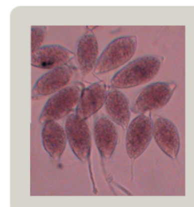
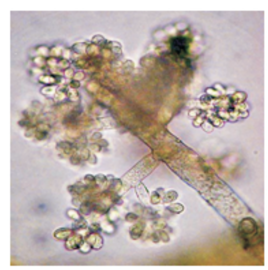
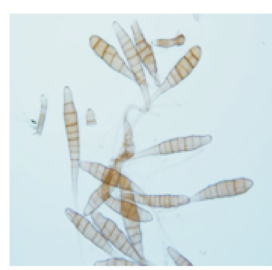
Root rot of capsicum	*Phytophthora capsici*		
Frogeye leaf spot of capsicum	*Cercospora capsici*		
Grey mould	*Botrytis cineария*		
Early blight	*Alternaria solani*		

3. INTEGRATED DISEASE MANAGEMENT IN VEGETABLE CROPS UNDER POLYHOUSE CONDITIONS/PROTECTED AGRICULTURE

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Abstract: Protected cultivation has partial control over plant micro-climate to alleviate one or more of abiotic or biotic stress for optimum plant growth. It has emerged as a useful technology for raising vegetables, flowers and others high valued as well as perishable crops. In modern agriculture, protected structures like polyhouse have an extreme potential for enhanced production with higher productivity and quality than the open field produce. However, the problems of low yield and poor-quality marketable produce is also faced due to various constraints viz. diseases, insect-pests, lack of planting materials and management technology, out of which various diseases inflict huge losses in important corps i.e. cucurbits, tomato, capsicum and other crops. Sometimes minor diseases under field conditions were observed to become major constraints under protected cultivation due to constant congenial environmental conditions. Once the pathogens enter and establish in the protected structures, these are difficult to eradicate and cost of controlling such established diseases can be high and in some cases prohibitive. In this article, the major diseases and their integrated management are described for different vegetable crops under polyhouse conditions.

Introduction

The crop pests, weeds and diseases constitute a major constraint to increase food production causing a loss of approximately 30% of the total crop produce. Growing of vegetables under protected environment is becoming popular in Himachal Pradesh due to prevalence of diverse climate and cool summer months suitable for off-season vegetable crops. Tomato, capsicum and cucumber are the major vegetable crops grown under protected cultivation and these crops are highly affected by diseases *viz*.,downy mildews on cucurbits; and bacterial wilt, collar rot, powdery mildew, early blight, phytophthora blight etc. in tomato and capsicum. Sometimes diseases of minor importance under field conditions become major constraints under protected cultivation due to constant and consistent congenial environmental conditions. It warrants the application of judicious disease management practices.

In general, the commercial vegetable growers, especially under protective cultivation apply high doses and more number of chemical sprays than the recommended ones which leads to several problems as enlisted below:

- Pathogen resurgence and development of resistance to pesticides.
- Pollution of water, air and soil.
- Pesticide residues in plant products leading to toxicity problems in animals, including human beings.
- Direct hazard to human due to acute or chronic poisoning and death.

The increasing costs of fungicides and uncertainty of effectiveness of these chemicals pose the problem of long term and ecological sound disease management. A study conducted in the Himalayan foothills during COVID-19 pandemic due to pollution free atmosphere indicated that it results in improvement in direct radiant energy positively and increased the gross primary productivity. (Pokhariyal et al., 2021). This warrants their management through integrated management approach i.e. management strategies base on sound ecological principles with the aim to prevent the establishment of pests and diseases in the greenhouse environment to minimize their development and spread. It infers that the management should involve different biological options i.e. host resistance, chemical, biological, physical and cultural measures etc. to give stable long-term disease control.

Integrated disease management practices utilize all suitable techniques and methods in a compatible manner to keep diseases below the economic injury level. A successful disease management program requires extensive knowledge of crop production requirements and the ability to recognize the key diagnostic symptoms and signs of diseases.

Diseases can reduce the quantity and quality of plants and their products resulting into direct financial losses to producers. The cost of controlling plant disease management after their establishment can be high and may become prohibitive therefore, preventative approaches may be necessary and needs to be applied to the next crop. Effective disease management may become deciding factors between success and failure of a greenhouse business. Further for effective decision making in Agriculture, forecasts of weather parameters were found useful and profitable (Rana et al., 2013).

The effective and economic management of disease depends upon:

- Accurate diagnosis of disease
- Knowledge of source of initial inoculum and its spread
- Environmental conditions during the host-pathogen interaction and cropping seasons.
- Integration of effective management practices

Steps to prevent disease problems in greenhouses:

- Sanitizing tools, shelves, stands, pots and medium of usage
- Monitoring humidity and temperature to discourage disease-friendly zones
- Providing proper ventilation and increasing air circulation
- Irrigating plants at their bases or crowns to prevent water splashing
- Cleaning surfaces regularly to discourage spore germination
- Giving plants a plenty of space for air circulation
- Checking plants daily for signs and symptoms of disease, discoloration or other unusual developments
- Quarantining new plants to ensure their disease-free status

Steps for integrated disease management in greenhouses

- Maintenance of proper hygiene
- Restricted entry of the pathogen
- Start with disease-free seeds, plants and planting material
- Control the environment
- Inspect plants regularly
- Waste management
- Control of insects and weeds
- Judicious use of fungicides and other management practices

Important diseases of vegetable crop

Damping off in nursery

Symptoms: Damping off occurs in the nursery. The poor seed germination is the first indication of the disease due to rotting of seed and is known as pre-emergence damping off. The second phase of the disease appear after seedling emergence and is known as post emergence damping off. The fungus infects on the hypocotyl, basal stem, and the developing tap-root. Stem of infected seedling becomes thin and constricted near soil line and the seedlings topple down and die.

Causal agent: The disease is mainly caused by *Pythium* and *Phytophthora* spp. under wet condition and species of *Rhizoctonia, Fusarium, Sclerotium etc.* under dry conditions.

Management

- The nursery raising site should have ample sunshine throughout the day and the site may be changed periodically
- Solarization of nursery soil by covering it with transparent polythene sheet during summer month for 45 days, is highly effective
- Drench the nursery bed with formalin @ 1 litre dissolved in 10 litres of water, 15 days before sowing.
- Pre sown soil application of bioagents (*Trichoderma* spp.) along with FYM
- Use of healthy and pathogen free seed for sowing
- Treat the seed with captan/metalaxyl MZ/mancozeb @ 2.5g/kg seed
- Sow the seed in rows 5-10 cm apart in 5 cm raised beds

- Drench the nursery seedlings with mancozeb/captan/metalaxyl MZ (@2.5g /L of water on the initiation of first symptom.

Bacterial wilt of solanaceous crops

Symptoms: The disease appears at the adult plant stage as drooping of upper leaves followed by sudden wilting of whole plant within 1-2 days without yellowing of leaves. The wilted plants remain green for long time without shedding of leaves. The vascular bundles show brown discoloration Presence of bacteria in the infected plant can be reduced by dipping the cut edge of diseased stem or branch in a glass of clean water and by observation of milky ooze. The disease appears in patches in the field and attains serious propotions after the onset of monsoon.

Causal agent: *Ralstonia solanacearum*

Management

- Grow disease resistant variety such as Palam Hybrid 1 *etc.*
- Raise nursery in healthy soils
- Solarization of nursery soil by covering it with transparent polythene sheet during summer month for 45 days
- Apply bio-agents viz. *Pseudomonas fluorescens*in soil along with FYM before sowing
- Root dip treatment of seedlings with 200 ppm solution of streptocycline before transplanting
- Drench the plant roots in the solution of 2g streptocycline and 30g copper oxychloride in 10 litres of water
- Follow 3-4 years crop rotation with non solanaceous crops
- Soil sterilization with formalin @ 1 litre/10 litre of water

Diseases of Tomato

Buckeye rot

Symptoms: Primarily the disease infects fruits formed near the soil surface as small brown round spots that enlarge rapidly into a chocolate-brown zonate lesions. Affected ripe fruits appear water-soaked and usually remain smooth with internal rotting. The disease spreads through rain splashing.

Causal agent: *Phytophthora nicotianae* var. *parasitica*

Management

- Remove and destroy the crop debris after harvest
- Soil application of bioagents (*Trichoderma* spp.) mixed with FYM before sowing
- Remove lower leaves near the soil surface and stake the plants with wooden sticks or ropes to avoid contact of fruits and leaves with soil surface
- Avoid excess humidity in the polyhouse
- Spray crop with copper oxychloride (0.3%) or mancozeb (0.25%) at 10 days interval or a combo-product of cymoxanil (8%) + mancozeb (64%) (@ 0.25%) at 15 days interval with the appearance of disease
- Grow resistant varieties like Yashwant-A2

Late blight

Symptoms: Initial symptoms appear on leaves as water soaked dark green spots which turn brown, enlarge and give blighted appearance. In wet weather, white fungal growth appears on the lower side of the blighted leaf surface. Disease appears as greyish green water-soked lesions on the fruits which later enlarge and turn dark brown with rough surface. The disease occurs only in moist weather with cool nights and moderately warm days.

Causal agent: *Phytophthora infestans*

Management

- Stake and prune the tomatoes to promote air movement and reduce leaf wetness
- Destroy the diseased plant and rotten fruits

- Maintain proper drainage
- Apply various amendments viz. vermi-compost, FYM and poultry manure along with paddy straw, plastic, leaf litter mulches etc
- Soil treatment with bioagents i.e. *Penicillium aurantiogriseum, P. veridicatum, Aspergillus terreus, T. viride* etc.
- Spray Ridomil MZ (metalaxyl+ mancozeb / Moximate (cymoxanil + mancozeb) @0.25% and Indofil -45(mancozeb)/ Antracol (propineb)/Kavach (chlorothalonil) @0.25%

Early blight

Symptoms: Dark brown to brown black and round spots start appearing on the lower leaves and concentric rings develop on the spots which show "target board" appearance. The spots are surrounded by yellow halo and in severe infections, leaves turn yellow and drop. Disease symptoms also appear on stems and may produce stem cankers. On fruits large, sunken, black target spots develop at the stem end.

Causal agent: *Alternaria solani* and *A. alternata*

Stemphylium blight

Symptoms: Brown to black specks appear on older leaves and young leaves which enlarge into angular to oval brown spots with grey centres surrounded by yellow halo and several spots coalesce. Leaves turn yellow, become brittle and drop out. In severe cases entire plant gets affected.

Causal agent: S*temphylium lycopersici*

Management (both for the early and Stemphylium blight)

- Remove lower leaves after the first fruit sets and also remove the affected leaves
- Spray the crop with 14-days old compost extract (CEX) in the ratio of 1:5 compost to water (*v/v*) It is highly effective.
- Use *Bacillus subtilis /Trichoderma harzianum, T. viride /Pseudomonas fluorescens a*s soil application.
- Seed treatment with Thiram (3 g/kg).
- Spray the crop with Bordeaux mixture at weekly interval before the onset of disease or Indofil Z-78 (zineb) (0.25%) / Score (difenoconazole) (0.05%) /Indofil M-45 (mancozeb) (0.25%)/ Blitox (copper oxychloride) (0.3%) at 10-15 days interval.

Septoria leaf spot

Symptoms: Disease usually appears on the lower leaves as circular spots of ~ l/8 inch in diameter, with dark margins and grey centres with the tiny black dots. Under severe infection numerous spots join together, and the leaves turn yellow and drop. Defoliation reduce fruit yield and quality as the exposed fruits become prone to sunscald. Rainy weather with moderate temperatures favour disease development and a rapid spread of the disease to the upper leaves.

Causal agent: S*eptoria lycopersici*

Management

- Remove all plant debris and bury deep in the soil
- Deep ploughing of the field and a 3-4 year crop rotation with non-solanaceous crops
- Staking increases air circulation and helps to keep the leaves dry and thus reduces favorable conditions for infection
- Mulching acts as a barrier between the soil and the tomato and prevents splashing of spores onto the lower leaves
- Spray the crop with mancozeb @ 0.25% or carbendazim @ 0.1%.

Powdery mildew

Symptoms: White powdery spots appear on leaves, stem and branches. High temperature and dry conditions favours the disease. Sometimes, depending upon the causal agent involved yellow patches

develop on leaves which later become necrotic.
Causal agent: *Oidium neolycopersici and Leveillula taurica*

Management

- Grow the plants with wide spacing
- Follow strict greenhouse hygiene throughout the growing season
- Follow a thorough after harvest clean up and dispose of all crop debris off-site or by burning or burying in a landfill
- Improve greenhouse climate to reduce relative humidity and increase air circulation
- Application of conidial suspensions of the hyper-parasites *Ampelomyces quisqualis, Sporothrix rugulosa, Tilletiopsis minor* and *Verticillium lecanii* help to control the disease
- Spray Contaf/Sitara (hexaconazole) @ 0.1% or Tilt (propiconazole) @ 0.1%/Score (difenconazole) @ 0.05%.

Bacterial canker
Symptoms: Infected plants start wilting from the lower leaves. The outer edges of the leaves wilt, turn brown and die, sometimes the wilting is observed on leaflets on one side of plant. The disease progresses upwards in the plant. Spots on fruits begin as white, slightly raised blisters which break open later on and show a rough yellow to brown surface with white halo. On splitting the stem, light yellow to brown streaks can be observed on vascular tissues. The center of the stem may have a yellow to red-brown mealy appearance and yellowish bacterial ooze can be squeezed from infected stems. There may be formation of above-ground roots on the stem.
Causal agent: C*orynebacterium michiganense* pv. *michiganense*

Management

- Remove and destroy the crop debris after harvest
- Rogue out and destroy the infected plants to avoid spread of the disease in the crop
- Use disease free healthy seedlings for transplanting
- Follow 2-3 year crop rotation
- Spray the crop with Copper oxychloride (0.3%) + streptocycline (100ppm) at 15 days interval with appearance of the disease

Diseases of Capsicum

Powdery mildew
Symptoms: Pluffy, white patches of powdery growth appear on the underside of leaves which later on turn brown. The abaxial leaf surface may appear normal or have diffused, yellow-coloured patches corresponding to the mildew colonies on the lower surface. Severely affected leaves become pale yellow green, turn brown and fall prematurely.
Causal agent: *Leveillula taurica*

Management

- Transplant the plants at proper distance and follow strict greenhouse hygiene throughout the growing season
- Conduct a through year-end clean up and dispose of all crop debris off-site or by burning or burying in a landfill.
- Improve greenhouse climate to reduce relative humidity and increase air circulation
- Apply conidial suspensions of hyper-parasite viz. *Ampelomyces quisqualis, Sporothrix rugulosa, Tilletiopsis minor* and *Verticillium lecaniito* greenhouse cucumbers
- Spray hexaconazole, propiconazole, azoxystrobin + tebuconazole @ 0.1% / difenoconazole @ 0.05%

Phytophthora root rot

Symptoms: The above ground symptoms of phytophthora root rot include chlorosis, stunting, and sudden wilt. Invasion of roots and stems below soil line show a soft, water soaked, blackish brown, decay which ultimately involves all tissues. Diseased plants are easily pulled from the soil, but invariably the cortex of the tap root and lateral root slough off and remain behind. Stem tissue of affected plants may be discoloured. Girdling of plant at the soil level and results in sudden wilting and death of the plant.

Causal agent: *Phytophthora capsici*

Management

- Grow crop on raised and well drained beds
- Destroy rotten fruits
- Plant peppers on raised beds (at least 22 cm high)
- Use of bio-control agents such as *Bacillus subtilis, B. vallismortis, Paenibacillus* and mycorrhizal inoculants
- Pepper seed treatment with biomass of *Gliocladium virens* and *Burkholderia cepacia*
- Seed treatment with Ridomil MZ (metalaxyl+mancozeb) (2g/kg seed)
- Spray with Ridomil MZ (metalaxyl+mancozeb)/Curzate (cymoxanil+mancozeb)@ 0.25% and mancozeb/propineb/chlorothalonil @0.25%
- Silica amendment of nutrient solutions is effective

Grey mould

Symptoms: Disease initiates from flower petals and the fungus grows from fading flower petals into developing fruit. On fruits, symptoms appear as water-soaked spots that expand into large yellowish-green to greyish brown irregular lesions of soft and spongy texture. On the leaves, grey coloured irregular water soaked areas appear which enlarge and coalesce resulting in withering of leaves. On stem, symptoms appear as small orange-brown lesions which on expanding cover entire stem and lead to its girdling.

Causal agent: *Botrytis cinerea*

Management

- Remove and destroy fallen leaves and other plant material
- Spray thiophanate methyl or carbendazim (0.1%)

Fusarium wilt

Symptoms: Initially, leaves of infected plants show vein clearing and turn yellow. Slowly, the leaves droop and finally the entire plant dries up. Brown coloured vascular tissues are visible when the stem is cut across near the soil line. The infected roots become dark and rot.

Causal agent: *Fusarium oxysporum* sp. *lycopersicae*

Management

- Follow long crop rotation of 4-6 years using non-solanaceous crops
- Soil application of bioagents (*Trichoderma* spp.) along with FYM before sowing is beneficial
- Apply farmyard manure in acidic soils
- Use recommended (resistant) varieties and certified disease-free seed
- Treat the seed with carbendazim @ 2.5g/kg
- Dip the seedlings before transplanting followed by drenching with carbendazim @ 0.1% after 15 days of planting

Anthracnose/Fruit rot

Symptoms: Initial disease symptoms appear as water-soaked lesions which become soft, slightly sunken, and later turn tan coloured. The lesions cover most of the fruit surface with multiple lesions. The surface of the lesions become covered with wet, gelatinous spores arising from salmon-coloured

fungal fruiting bodies (acervuli) with numerous black spines (setae). Concentric rings of the acervuli are common on the fruit spots.
Causal agent: *Colletotrichum capsici*

Management

- Use disease free seed and treat it with hot water at 52°C for 30 minutes in a water bath or carboxin @ 2.5g/kg seed.
- Spray mancozeb @ 0.25%/ carbendazim @ 0.1%/mancozeb + carbendazim @ 0.25%.
- Destroy the crop debris.

Cercospora leaf spot
Symptom: The disease initiates as small light brown spots on leaves, which later become upto 1cm in diameter having white centre and dark margin. Several spot coalesce and the leaves become blighted. There is premature leaf fall hence, it affects the yield drasticlly.
Causal agent: *Cercospora capsici*

Management

- Follow crop rotation.
- Remove and destroy infected leaves.
- Spray the crop with benomyl (0.05%) or hexaconazole (0.2%) or azoxystrobin + tebuconazole (0.1%)

Diseases of Cucumber

Downy mildew

Symptoms: Generally, the spots being delineated by the leaf veins, have an angular appearance. Cool-wet weather favours initiation of downy mildew. Young pale green spots appear on abaxial leaf surface which turn yellow and brown before the tissue dies. Purplish downy fungal growth appears on the lower side in moist weather and generally several spots coalesce together. Infected leaves usually wither and die. Premature death of vines may also occur in severe infection.
ausal agent: *Pseudoperonospora cubensis*

Management

- Avoid over watering and remove infected plants
- Wider spacing and application of potassic fertilizers helps in reducing the disease severity/ levels
- Spray of neem oil and bio-fungicides such as *Bacillus subtilis* is effective
- Spray the crop with Ridomil MZ (metalaxyl+mancozeb)/Curzate (cymoxanil+mancozeb) and mancozeb/propineb/chlorothalonil @ 0.25%.

Powdery mildew
Symptoms: Initially tiny dull-white fine colonies of the fungus develop on both leaf surfaces and other above ground foliage . Yellow spots may appear on upper leaf surfaces opposite to the powdery mildew colonies. The mildew colonies coalesce and produce superficial dull grey powdery mass and the infected leaves usually wither and die. Premature death of vines may occur in severe infection and dark brown cleistothecia develop late in the growing season.

Causal agent: *Sphaerotheca fuliginea* and *Erysiphe cichoracearum*

Management

- Plant the cucumber plants at sufficient spacing

- Follow strict greenhouse hygiene throughout the growing season
- Conduct a thorough year-end clean up and dispose of all crop debris off-site by burning or burying in a landfill.
- Improve greenhouse climate to reduce relative humidity and increase air circulation
- Application of conidial suspensions of the hyper-parasite *Ampelomyces quisqualis, Sporothrix rugulosa, Tilletiopsis minor* and *Verticillium lecaniito* greenhouse cucumbers
- Spray hexaconazole/dinocap/propiconazole/ @ 0.1% / difenoconazole @ 0.05%.

Anthracnose

Symptoms: Roughly circular, light brown to reddish lesions appear on cucumber leaves which later on turn tan to brown and oval in shape with dark brown dot like structures called acervuli. The centers of the lesions often crack and create a shot-hole appearance.

Causal agent: C*olletotrichum lagenarium*

Management

- Follow general sanitation and crop rotation.
- Use disease-free seed.
- Grow resistant varieties.
- Give alternate spray of azoxystrobin and benomyl (0.05%) at 15 days interval with the appearance of the disease.

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4. VIRAL DISEASES AND THEIR MANAGEMENT UNDER PROTECTED ENVIRONMENT

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Abstract: Protected cultivation of vegetable crops during the off-season is a popular venture among the farmers of Himachal Pradesh and different vegetables are grown across the state under protected cultivation which ensures the sustainable income of farmers. The popularization of protected cultivation and consequent use of hybrid seeds has led to the escalated incidence of the viral diseases in the state. A number of viral species belonging to genera potyvirus, tospovirus, tobamovirus and cucumovirus are reported to induce variety of symptoms including vein banding, vein clearing, ringspots *etc.* Challenge lies ahead for plant pathologists as viral diseases cannot be directly controlled with the use of chemicals. However, ensuring supply of healthy seeds and planting material, monitoring of population levels of insect vectors and timely and safe roughing of diseased plants can ensure healthy crops.

Introduction

Protected agriculture or polyhouse cultivation of vegetable crops during off-season is proving a boon for the small and marginal farmers of Himachal Pradesh. Major vegetable crops cultivated under protected agriculture include Capsicum (Shimla mirch), tomato and cucumber. In addition to it, some exotic vegetables like asparagus, leek and some leafy vegetables are also grown whereas, among the ornamentals lilium, gerbera and chrysanthemum are the most common under protected environment. The protected agriculture crops are grown under an environment that favours the growth of the plants as well as provide congenial conditions for the pathogenic organisms like fungi, bacteria, viruses and nematodes. Among these biotic agents the viral diseases have become one of the most important production constraints in capsicum, tomato and cucumber under protected cultivation. Worldwide, the viral diseases result in huge losses (~several billion dollars) and pose a major threat to sustainable and productive agriculture system (Mumford et al., 2016). Most of the ornamentals, being vegetatively propagative, are more prone to the drudgery of viral diseases. The popularization of protected agriculture venture and the use of hybrid seeds has led to the escalated incidence of the viral diseases in the state (Sharma et al., 2016). Surveys of the protected agriculture structures revealed that the major disease symptoms in the crops were in the form of mosaic, mottle, chlorosis, upward or downward curling of the leaves, puckering, deformation and reduction of leaf lamina along with stunting of infected plants in some areas (Sharma and Patiyal, 2011). These viral diseases have no direct control except for their timely detection , use of pathogen free planting material, control of vectors and use of resistant genotypes. Once these pathogens enter the protected structures, it becomes very difficult to manage them due to the prevalence of the most congenial and permanent environmental conditions resulting in regular failure of crop. The effective management of viral diseases require the knowledge about these pathogens among the farmers and protection personnels involved in their management. In general, the plant disease management begins with disease diagnosis and ends up with selection of effective and economic management practices to safeguard the interest of the growers and the consumers along with the protection of environment. An assessment study indicated that the shift towards off-season vegetable production, better control of diseases, insects, and pests and implementation of adaptation measures to offset climate change can enhance climate resilience in mountain regions (Rana et al., 2021).

Important genera of plant viruses infecting crops under protected cultivation

Potyvirus

Members of this genus consist of positive-strand RNA (+ssRNA) viruses and belong to family *Potyviridae* and the type species of the genus is *Potato virus Y*, PVY (Virus Taxonomy, 2021).

Genome of viruses of this genus encodes single open reading frame and follow polyprotein strategy. The polyprotein is processed into ten smaller proteins (Chung et al., 2008). Potyviruses account for about thirty percent of the currently known plant viruses viz. begomoviruses. The members of this genus may cause significant losses in agricultural, pastoral, horticultural, and ornamental crops. Mechanical and insect vectors are known modes of its transmission and more than 200 species of aphids are reported to spread potyviruses (Virus Taxonomy, 2021).

Tobamovirus

Viruses belonging to genus Tobamovirus are positive-sense single-stranded RNA (+ssRNA) viruses having wide host range. The type member of genus *Tobacco mosaic virus* (TMV), in the family *Virgaviridae,* was first described by Mayer in 1886 (Mayer, 1886). These viruses mainly infect vegetable crops in the family *solanaceae* and *cucurbitaceae* (Smith and Dombrovsky, 2019). In addition, ornamental and medicinal plants and weeds are also infected. A worldwide infection of the cucurbitaceous plants has occurred due to the spread of a tobamovirus *i.e Cucumber green mottle mosaic virus* (CGMMV) which was first reported by Ainsworth in 1935 (Rajamony et al., 1990; Sugiyama et al., 2007). The viruses of this genus are not vector-transmissible and when these are seed transmitted, the embryo is not affected (Virus Taxonomy, 2022).

Tospovirus

Tospoviruses belong to family *Bunyaviridae* and genus Tospovirus (Virus Taxonomy, 2022). The genus is unique in the family *Bunyaviridae* as it constitutes the viruses which infect plants (Oliver and Whitfield, 2016). The member viruses of the genus are enveloped isometric RNA viruses with a tripartite genome having small (S), medium (M), and large (L) segments of ssRNA. They are transmitted by thrips (*Thysanoptera*) in a propagative manner and are one of the most important plant virus groups infecting a wide range of economically important crop plants all over the world (Pappu et al., 2009). Tospoviruses have emerged as serious viral pathogens affecting the cultivation of several field and horticultural crops (Varma et al., 2002). In nature, the tospovirus member species are transmitted in a persistent propagative manner by thrips species in the order Thysanoptera (Hogenhout et al., 2008).

Cucumovirus

The Cucumovirus genus of family *Bromoviridae* is a member of the 'supergroup', which includes both plant and animal viruses (Roossinck, 1997). Viruses belonging to the genus cucumovirus are positive-sense single-stranded RNA (+ssRNA) having wide host range. The type member of genus *i.e. Cucumber mosaic virus* (CMV) has an extremely broad host range which includes plants in 85 families and more than 1000 species (experimentally). The other cucumoviruses have narrower host ranges. Cucumoviruses are transmitted in a non-persistent manner by over 80 species of aphids belonging to more than 30 genera (Virus Taxonomy, 2022). Recent evidence expands the CMV host range to other kingdoms and included oomycetes (kingdom Stramenopila), ascomycetes and basidiomycetes (kingdom Fungi) (Andika et al., 2017; Mascia et al., 2018).

Begomovirus

Begomoviruses constitute a group of plant viruses which have emerged as a serious threat to the production of many vegetable and other crops (Navas-Castillo et al., 2011). Begomoviruses constitute of both the Old (both genome types, monopartite and bipartite) and New World viruses (mostly bipartite genomes, with few monopartite genome viruses) (Brown et al., 2015). The genomes of bipartite begomoviruses consist of two components which are referred to as DNA-A and DNA-B. Sometimes a circular ssDNA satellites of approximately half (betasatellites and alphasatellites) or quarter (deltasatellites) begomovirus size are associated with some begomoviruses. Begomoviruses are reported to be transmitted by the whitefly *Bemisia tabaci* which is believed to be a cryptic species complex (De barro et al., 2011). However, many begomoviruses are differentially transmitted by different species of the *B. tabaci* complex (Fiallo-Olivé et al., 2020). It is also reported that some begomoviruses are experimentally transmissible by mechanical inoculation, although most require either Agrobacterium-mediated transfer (agro-inoculation) (Rojas et al., 2005).

3. Classification of symptom variability

Mosaic: Appearance of dark green and light green pattern (may be yellow/ golden).
Mottle: Mottle is a diffused form of the mosaic symptoms in plant leaves in which the dark and light green areas are less sharply defined. This term is frequently used interchangeably with mosaic.
Vein-clearing: A symptom of virus-infected leaves in which veinal tissue is lighter green than that of healthy one. Vein-clearing involves onset of chlorosis of veins and veinlets leaving the rest of the leaf green.
Vein-banding: *Vein-banding* usually precede mosaic and mottle formation. The areas along the veins become either dark green or yellow due to virus infection.
Chlorosis: The loss of chlorophyll from the tissues of a plant, resulting from microbial infection. In virus diseases, *chlorosis* is the most common in leaves and other green parts.
Yellowing: A symptom characterized by the turning yellow of plant tissues that were once green.
Leaf curl: Plants are severely stunted with shoots becoming erect. Leaflets are reduced in size and pucker. Leaflets curl upwards, become distorted, and have prominent yellowing along margins and/or interveinal regions.
Ringspots: Appearance of single or concentric rings of discoloration or necrosis on infected leaves or fruits, the regions between the concentric rings being green.
Stunting/ Dwarfing: The infected plants or its parts do not attain the normal size due to virus infection than the normal healthy plant.

Most common symptomatology and viral species associated with diseases of tomato, capsicum and cucumber

- Mosaic : *Tobacco mosaic virus (TMV), Cucumber mosaic virus (CMV), P*otato virus Y (PVY), *Tobacco virus etch* (TEV), *Pepper mottle virus (PeMV), Pepper mild mottle virus*(PMMV), *Pepper severe mosaic virus (PSBMV), Water melon mosaic virus-2* (WMV-2)
- Tospo viruses: *Tomato spotted wilt virus* (TSWV), *Capsicum cholorotic virus*(CaCV), *Groundnut bud necrosis virus* (GBNV)
- Leaf curls: *Tomato leaf curl virus (ToLCV), Tomato yellow leaf curl virus (TYLCV), Chilli leaf curl virus (ChiLCV)*

Capsicum mosaic complex:

The mosaic is caused by many viruses like Tobamovirus i.e. *Tobacco mosaic virus, Pepper green mottle virus, Cucumber mosaic virus, Potato virus Y, Tobacco etch virus, Pepper mottle virus, Pepper severe mosaic virus, Pepper mild mottle virus* etc. These viruses spread among the plant through aphids and contact.

Tobacco mosaic and Pepper mild mottle virus spread through contact and seed contaminant but not by insects. *Potato virus Y, Tobacco etches* and*Pepper vein mottle virus* spread both by aphid vectors as well as contact. In contact spread, the cutting and pruning knives used for trailing the plants under polyhouse play an important role. This type of symptoms is caused by many viruses and is generally called as mosaic compex.

Cucumber mosaic virus

The diseased plants exhibit mosaic symptoms in the form of light and dark green areas on leaves. The virus is transmitted by aphids in non-persistent manner and may also through seed. Diseased plants remain stunted and do not bear normal fruits after one or two pickings.

Tobamoviruses (Tobacco mosaic and Pepper mild mottle)

The leaves of infected plant develop mild systemic mosaic and leaf crinkling. Severe symptoms such as distortion, rings, lines and necrotic spots develop on fruits of infected plants. The virus is transmitted through contact and the seed contaminant but not by insects. The main source of primary inoculum includes infected seed, crop debris, work benches and humans working in the polyhouses.

Potato virus Y, Tobacco etch, Pepper veinal mottle

These viruses cause mosaic, severe mosaic, shoe stringing, stunting of plants and fruit deformation. The virus survives in weeds and, volunteer plants in the absence of main host. The virus is transmitted by aphids in non-persistent manner.

Tomato spotted wilt virus

The tospovirus symptoms appear as chlorotic or necrotic rings, lines pattern, or spots on leaves, fruits and stems, along with necrotic streaks on stems. There is bronzing, curling, and wilting of leaves. The infected plants remain stunted and show necrosis of parts or whole plants. The symptoms vary with the type of host/ variety, organ affected and age of plant at the time of infection. Tomato plants show poor growth, leaf rolling, browning of leaves and wilting. The ringspots on fruits are very common. Tospoviruses are transmitted by many species of thrips (*Frankliniella occidentalis),* Tobacco thrips (*F. fusca),* Common blossom thrips *(F. schultzei),* Onion thrips (*Thrips tabaci)* and melon thrips *(T. palmi)*.

Water melon mosaic virus-2

The characteristic symptoms exhibited by WMV-2 virus infection under both natural and glasshouse conditions include vein clearing, vein banding, mild mosaic to yellow mosaic, blistering on leaves along with stunted growth of vines bearing small sized distorted fruits. The virus is reported to infect cucumber under mid-hill conditions of H.P.

Diseases caused by Geminiviruses

Tomato leaf curl virus

Tomato leaf curl is caused by *Tomato leaf curl virus* (ToLCV) and *Tomato yellow leaf curl virus* (TYLCV). The diseased plants remain stunted or dwarf. The leaflets of infected plants are rolled upwards and inwards. The leaves are often bent downwards, become stiff and thicker than the normal. Such leaves have a leathery texture and often with purple tinge to the veins on the underside. Young leaves are slightly chlorotic (yellowish). Flowers appear normal, however, the fruits, if produced are small, dry and unsalable. The diseased plants tend to be distributed randomly or in patches. ToLCV infection can be confused with several other tomato disorders such as tomato big bud, tomato yellow top, and physiological leaf roll and phosphate and magnesium deficiency.

Tomato and pepper leaf curl

The virus infected plants exhibit *Leaf curling* reduction of leaf size, and thickening of leaves, followed by bunchy growth of the branches or severe stunting of plants. Early infections of the plants may result in complete yield loss. The virus is transmitted by whitefly (*Bemisia tabaci*) in semi-persistent manner.

Management of viruses under protected environment

Successful crop management strategies require scientific understanding of nature of the causal virus(es) i.e. how viruses survive and spread between crops and across seasons. Unfortunately, plant viruses cannot be cured, hence their management is mainly aimed at prevention or the reduction of infection. There is no single approach for the management of all virus diseases since different diseases have diverse ecological and epidemiological considerations. Thus, a complete understanding of a virus patho-system in a given agro-ecosystem is vital for developing management strategies once a plant is infected by a virus usually it remains infected for the entire life of the plant

A) Prerequisites for virus disease management

a. Correct virus identification and diagnosis
b. Understanding pathogen biology
c. Disease epidemiology
d. Development and evaluation of a management strategy

B) Understanding the biology of the virus is necessary for effective disease management

1. Properties of the virus (virus structure and genetic material)
2. Host range
3. Vector (insect or other)
4. Sources of inoculum: Seed, weeds/other reservoir hosts, old crops and insects
5. Means of survival in the absence of the economic hosts

Virus Disease Management

Management of viruses under protected agriculture conditions is a three tier strategy.

1. Nursery raising and management

a. Raise nursery under protected structure to avoid nursery infection.
b. Procure seedlings from healthy nursery only

2. Polyhouse hygiene

a. Surroundings
   i. Provision of double door in polyhouse
   ii. Focuses on removal of virus inoculum vector source etc.
b. Self (workers)
   i. Use of separate clothes/ aprons (white only) by workers
   ii. Avoid yellow clothing or utensils as these attract whitefly adults.
c. Tools: Use of clean tools

3. Crop management

i. Pre crop
ii. During crop
iii. Post crop

Virus management Strategy

1. Plant, Polyhouse and surrounding hygiene (removal of infection foci)
2. Raise healthy nursery or procure seedlings from reliable resources (reduction in initial inoculum).
3. Establish a minimum two month crop free period during the summer, preferably from mid-June to mid-August.
4. Avoidance of virus & vector infestation in the polyhouse.
   a. Use of sterilized knife or scissors during pruning and training of plants to avoid virus spread (contact transmitted).
   b. Remove and destroy all infected plants.
   c. Monitor vector population with yellow/ blue sticky traps.
   d. Use of insecticides at regular interval to avoid vector.
   e. Use of resistant varieties if available.

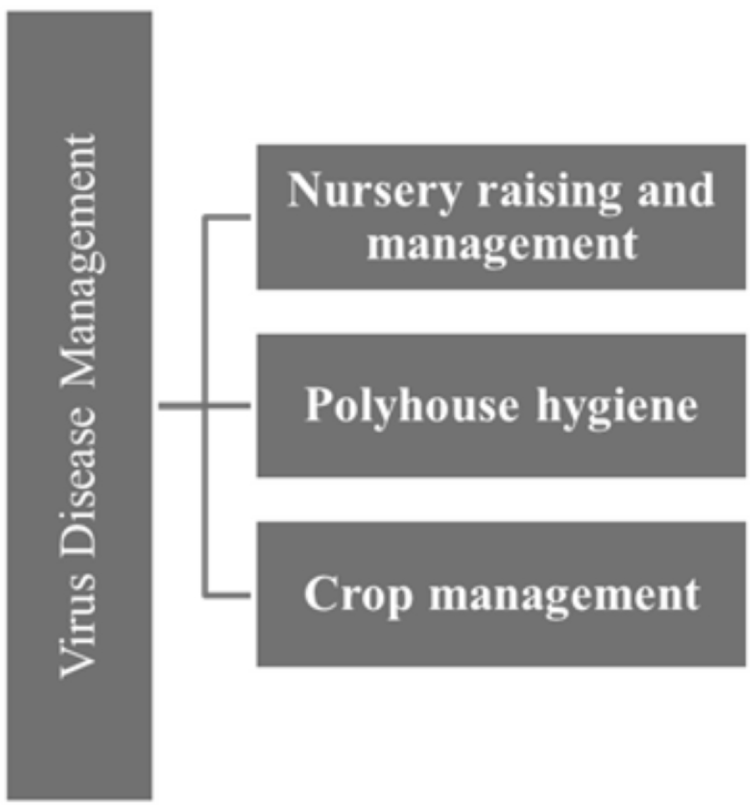
Key message for success in management of virus diseases

a. Farmers education about viruses and viral diseases is key to success
b. Virus infection cannot be detected visually in the seedling stage of crop, so use of healthy nursery is the first pre-requisite for success of the crop.
c. Plant once infected cannot be cured
d. No direct control of plant virus diseases
e. In polyhouses, only hybrids are grown and almost all hybrids are susceptible to one or the other virus in various crops so viable option of their management includes avoidance, protection & host resistance only.

Table 4.1: Viral diseases and their mode of transmission vis-à-vis protected cultivation in H.P.

Viral Species, Genus	Disease	Mode of transmission
Tobacco mosaic virus (TMV), Tobamovirus	Mosaic	Contact/Seed
Cucumber mosaic virus (CMV), Cucumovirus	Mosaic	Contact/Mechanical Means
Potato virus Y (PVY), Potyvirus	Mosaic	Contact/Aphid
Tobacco virus etch (TEV), Potyvirus	Mosaic	Contact/Aphid
Pepper mottle virus (PepMoV), Potyvirus	Mosaic	Aphid/Contact
Pepper mild mottle virus (PMMoV), Tobamovirus	Mosaic	Contact/Seed
Pepper severe mosaic virus (PepSMV)	Mosaic	Aphid/Contact
Tomato spotted wilt virus (TSWV),Tosposovirus	Ringspots, wilt	Thrips
Capsicum cholorotic virus (CaCV), Tosposovirus	Chlorosis	Thrips
Groundnut bud necrosis virus (GBNV), Tosposovirus	Bud necrosis	Thrips
Tomato leaf curl virus (ToLCV),Begomovirus	Leaf Curl	Whitefly
Tomato yellow leaf curl virus (TYLCV), Begomovirus	Leaf Curl	-
Chili leaf curl virus (ChiLCV), Begomovirus	Leaf Curl	Whitefly

Figure 4.1:Diagrammatic representation of key management points for virus disease management under polyhouse cultivation



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5. BIOLOGICAL CONTROL OF VEGETABLE DISEASES UNDER PROTECTED CULTIVATION

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Abstract: Agriculture in greenhouses and protected structures offer a unique niche for the development and use of biological control agents (BCAs). Among the commercial biocontrol products available, very few have applications in nurseries or polyhouses; and many were specifically developed against the soil-borne pathogens viz. *Pythium, Fusarium* and *Rhizoctonia* etc. which are major greenhouse pathogens. The use of biocontrol is more prevalent and beneficial in greenhouse and protected structures than in field crops, even though greenhouses account for only 0.02% of the area under agriculture. The biological control industry in greenhouse production is strong and it is still progressing. External drivers and internal support, may result in reduced pesticide use in greenhouses, and biological control is believed to become the cornerstone of pathogen management strategies, in many greenhouse vegetable crops. With much research being conducted on these strategies in greenhouses, of use and efficacy of biological control agents have a bright future and BCA's will certainly act as boon for the eco-friendly management of different diseases of vegetable crops under protected conditions. Keeping this in view, biological control management strategies for vegetable diseases in protected structures is being discussed.

Introduction

Biological control of plant pathogens is an established sub-discipline of Plant Pathology. Its beginning can be traced back to over 70 years. However, it was not until the early 1960s that theory and practice was integrated in the proceedings of the first biocontrol meeting. Over the past 20 years, the research efforts in this area have increased dramatically and over 40 biocontrol products have been launched for commercial use during the last decade but still, it constitutes a meagre fraction of the total number and sales of chemical fungicides in the field, vegetable and tree crops (Paulitz and Bélanger, 2001).

Agriculture in greenhouses and protected structures offers a unique niche for the development and use of BCAs. Of the commercial biocontrol products available, very few have applications in nurseries or greenhouses; and many were specifically developed against the soil-borne pathogens viz. *Pythium, Fusarium Sclerotinia sclerotiorum* and *Rhizoctonia etc.* which are major greenhouse pathogens. The use of biocontrol is more common in greenhouse and protected structures than in field crops, even though greenhouses comprise for only 0.02% of the total area under agriculture. Biological control management strategies for vegetable diseases in protected structures is being discussed in the present article. The Indigenous Technical Knowledge (ITK) *viz* use of Ramban (*Agave americana*) in paddy field, plantation of bana plant (*Vitex nigundo*) alongside of paddy nursery against insects and diseases, use of ankharein leaves to control rice hispa, use of lantana, eupatorium and eucalyptus plant leaves to control potato tuber moth during storage of potato have been reported climate resilient technologies for disease and insect management (Rana et al., 2018).

Common diseases in greenhouse-grown vegetables:

Fungal diseases (Celik and Gocmen, 2009)

- Grey mould (*Botrytis cinerea* Pers.)
- Late blight of tomato [*Phytophthora infestans* (Mont.DeBary)]
- Cucurbit downy mildew (*Pseudoperonospora cubensis* Berk. and Curt.)
- Wilt and root rot diseases (*Fusarium* spp., *Verticillium* spp., *Rhizoctonia solani*, *Phytophthora* spp., *Pythium* spp., *Alternaria* spp., *Sclerotinia* spp.)
- White mold [*Sclerotinia sclerotiorum* (Lib) De Bary]
- Cucurbit powdery mildew [*Erysiphe cichoracearum* (D.C.)], [*Sphaerotheca fuliginea* (Schlech).

- Powdery mildew of solanaceae [*Leveillula taurica* (Lev.) Arn. syn. *Oidiopsissicula* spp.
- Tomato leaf mold [*Fulvia fulva*, early leaf blight of tomato and eggplant *Alternaria solani*]

Bacterial diseases (Baysal et al, 2009)

- Tomato stem necrosis [*Pseudomonas* spp. and *Erwinia* spp.]
- Tomato bacterial wilt [*Clavibacter michiganensis* subsp. *michiganensis*]
- Tomato bacterial speck disease [*Pseudomonas syringae* pv. *tomato* (van Hall)]
- Pepper bacterial speck disease [*Xanthomonas vesicatoria* (Doidge) *auterin* Hoste, Kersters & Swings]
- Angular leaf spot of cucumber [*Pseudomonas syringae* pv. *lachrymans* (Smith & Bryan) Young, Dye]
- Bacterial wilt of solanacious vegetables (*Ralstonia solanacearum*)

Virus diseases Alfalfa mosaic, alfa movirus (AMV), Cucumber mosaic, cucumo virus (CMV), Potato X potex virus (PVX), Potato Y potyvirus (PVY), Squash mosaic comovirus (SqMV), Tobacco mosaic tobamo virus (TMV), Tomato yellow leaf curl bigemini virus (TYLCV), Tomato spotte wilt tospo virus (TSWV), Tomato mosaic tobamo virus (ToMV), Tomato black ring virus (TBRV), Tomato ring spot virus (ToRSV), Watermelon mosaic potyvirus (WMV–) and Zucchini yellow mosaic potyvirus (ZYMV) (Yucell et. al., 2013)

Reasons for unique disease problems in greenhouses:

The greenhouse environment is unique and provides more congenial conditions for the development of diseases (Paulitz and Anger, 2001).

- Most of the pathogens cannot be excluded from the greenhouse environment. Airborne spores enter through doors and screens whereas, soil-borne pathogens enter through dust, contaminated soil, shoes, tools, and/or equipment whereas, other pathogens are introduced on seeds or contaminated propagating material. Zoosporic pathogens enter through irrigation water, and insects carry fungal inoculum or transmit viruses.
- The temperature, light, and fertilizer regimes are optimized for maximum plant growth, but these conditions may also be congenial for pathogens also.
- The warmth and humidity, due to the water vapor transpired by the plants and the lack of air exchange with the outside, provide ideal conditions for foliar pathogens such as Botrytis grey mould and powdery mildews etc. Moreover, due to high energy costs, ventilation is often reduced to prevent loss of heat.
- Disinfested soil or soilless substrates such as peat or rockwool lack the microbial diversity and biological buffering present in a natural soil. Under such biological vacuum, soilborne pathogens such as *Pythium* and *Rhizoctonia* an quickly grow and spread.
- The life stages of plants commonly available in greenhouse nurseries are seeds, seedlings, and young transplants which are especially susceptible to many pathogens attacking juvenile tissue.
- High-density planting of greenhouse crops increases the relative humidity and enhances the chances of disease spread. Various management practices, i.e. pruning and harvesting, increase the spread and infection through wounds. Hydroponic systems, such as rockwool, nutrient film, or webb and flow, lead to varied disease problems. In closed re-circulating systems, zoosporic pathogens can easily spread in the water system.

Pesticides as a driver for biological control:

Global agriculture is supported by extremely large, and highly effective synthetic pesticide market worth US$31 billions and greenhouse growers can depend on it. Protected agriculture may have less and slow access to biological control in many areas of te world while the pesticides are readily available, easy to use and relatively cheaper. The popular media often reinforces the negative impacts of pesticides hence, growers are often forced to weigh up the cost of reducing their reliance on them with the benefits and strengths of intelligently used pesticides (Cooper and Dobson, 2007). Many countries have adopted strategies to reduce reliance on pesticides and encourage, or in some instances force, growers to consider other strategies in managing their pests, eg. the Pesticides Safety Directorate in United Kingdom lowered the registration fees associated with the development of biopesticides in 2006, in an effort to increase availability of reduced-risk of pesticides to growers.

Extremely active campaign has been undertaken against the users of pesticides in agriculture. Simultaneously, there is an increasing demand on efficient use of irrigation water. There is increase of area, production and market size of the greenhouse industy in many parts of the world and it has led to the increased use of biological control in these systems. These campaigns have successfully encouraged the use of IDM in the greenhouse industry as greenhouse structures are suited to use IDM, especially the biological control agents.

The success of biological control in greenhouses can be attributed to many factors. Greenhouses allow the grower to exclude many pests after rigorous sterilization process leading to cleaning of pathogenic organisms from the system. The conditions become ufavourable for the pathogen outside the greenhouse, once the pathogen is cleaned from the system and a new crop is planted. It is not easy for the pathogen to re-establish within the crop as there is no local population in the surrounding area. The estabishment of biological control organisms may be optimized as use of some pesticides, eg. fungicides may be reduced due to cultural practices that are inherent in greenhouse horticulture. If pesticide applications are required these are used locally and will have limited impact on adjacent growing units as these are isolated. Hence, these are the important drivers to adopt biological control in the greenhouse industry. Some new insecticides are commercially available for greenhouse growers with more tendency toward resistance development, compelling the growers to reduce the impact of the pesticide resistance (Van Lenteren, 2009). Moreover, there is reduced exposure of workers, environment, water and soil to extremely toxic chemicals and it is easier for the workers to release natural enemies. Biological control in greenhouses is at par with the conventional pathogen management and hence, may prove an attractive management strategy.

The uptake of greenhouse biological control:

There has been a huge shift to use IPM in greenhouses in many parts of the world, with the most striking example in Spain. Prior to 2006, biological control was adopted on a small scale and has changed dramatically in the growing season during 2007-2008, when 75% of 8000 hectares of sweet pepper in Almeria started to implement biological control for pathogen management (Van Lenteren, 2009). The well organized and well-orchestrated campaigns helped to bring this change in different management systems especially in food crops as per the demand of consumers and retailers. This change could be possible and successful through the whole supply chain for a persistent and consistent alteration of pathogen management practices. There must be availability of efficient biological organisms which may be mass reared or produced in a cost effective and efficient fashion so as to replace the conventional pesticides in greenhouses. Moreover, availability of these agents must be supported by an effective and non-destructive progression through any legal regulatory processes of area, state or the country.

Some promising biological control agents especially entomopathogens, are stalled in the registration process thus , preventing the use of an excellent and a viable alternative tool for the management of pests. It requires changes in greenhouse pathogen mangement in many regions of the world, experiencing campaigns of synthetic pesticides based on their harmful effects to consumers and creating a reaction in the market leading to a 'market pull'. It has led to a crisis in several parts of the world and forced vast and extensive changes in the mind set of growers for the use of pesticides. This crisis may affect many parts of the world and is a fore-warning to many systems suggesting that, the event of future change, understanding and developing alternative strategies including biological control for protected agriculture should be initiated early to avoid the disruption due to change in mind set and awareness regarding the use of synthetc pesticides.

Suitability of greenhouses for biological control:

Some of the conditions favouring disease are also suitable for the management of diseases with biological control agents. Temperature and relative humidity can be effectively controlled and just like the pathogen, biocontrol agents are also sensitive to evironmental conditions. Unfavourable environment in the field is considered as a reason for failure or inconsistent performance of BCAs whereas, the conditions in the greenhouse can be optimized for BCAs. eg. BCAs of powdery mildews are highly efficient at a relative humidity > 80%, a condition that is often and easily monitored under glasshouse conditions. The biological vacuum in soil substrates may favour the establishment of biocontrol agents, provided applied prior to pathogen introduction. The logistic and economics of applying biocontrol agents in the greenhouse are more favorable than under field. Greenhouse crops have a high economic value, and hence, absorb higher cost of inputs. The biocontrol agents can be directly applied to the growing mix, in fertigation system, sprayed on the plants, or applied to high value hybrid seed. Moreover, due to reduced area and high density of planting, inoculum requirement is tremendously less than in treating a field. Bio-control agents have a niche in the greenhoue market due to the absence of registered fungicides especially for greenhouse. Until 1999, no registered fungicides were available in Canada for the control of *Pythium* in greenhouse vegetable crops. High registration and development costs and lack of return on investment are deterrents to chemical companies in registering products for the relatively small greenhouse market. Crop management under greenhouse is highly intensive. Most of the fungicides require a re-entry period. Hence, workers are at greater risk of fungicide exposure in the greenhouse. Moreover, many greenhouse crops are continuously harvested and most of the highly toxic fungicides cannot be used. Breakdown, weathering, and wash-off of chemicals on the leaves or in substrates are lower in greenhouses than in the field, so fungicides may have a longer residual activity. The development of fungicide resistance in the pathogen may be enhanced by the intensive use and limited choice of fungicides in the greenhouse (Paulitz and Anger, 2001).

There is increasing societal concerns and awareness about the environmental and health effects of fungicides. A pesticide-free vegetable or floral product may give greenhouse growers a market advantage, especially during the main season when there is compeition with lower-cost field-grown produce. Technology-based intensive management is more practiced in greenhouse crops, and growers may prefer to adopt biological control than in less managed field crops.

However, greenhouse systems have some constraints that may limit the use of biocontrol practices. Greenhouse crop has high value and emphasis is laid on quality in floriculture, vegetable crops, and ornamentals, where acceptance level of damage and the thresholds for diseases are very low. Hence, if biocontrol agents are unable to perform with the consistency and efficacy comparable with fungicides their adoption may be less.

Products for biological control of soilborne pathogens:

There are over 80 products for biocontrol of pathogens worldwide. Most of these products are formulations either of the fungi *Gliocladium* and *Trichoderma,* the bacteria *Pseudomonas* and *Bacillus.* However, all of these products are not registered as biocontrol agents, but marketed as plant growth promoters, plant strengtheners, or soil conditioners as with such designations these products may be marketed with less stringent toxicology or efficacy testing than required for the plant protectants. Some countries have a regulatory framework for plant strengtheners eg, in Germany in 1998, 208 plant strengtheners (Pflanzenstrkungsmittel) were registered with der Biologischen Bundesanstalt, in 1998 as compared with 25 in 1991. These products include inorganic compounds such as SiO_2, $NaHCO_3$, and organic constituents such as compost, homeopathic compounds, and some microbial agents such as *Trichoderma harzianum, Bacillus subtilis, Pseudomonas* and *Pythium oligandrum.*

.**Biological control of greenhouse diseases:**

Some important biological control agents with their mode of action and target soil borne pathogens are given below:

Biocontrol Agents	Target Pathogen	Mode of Action
Bacillus spp. (*B. subtilis, B. amyloliquefaciens, B. firmus* and *B. pumilus*) *Coniothyrium minitans*	*Pythium spp., Fusarium spp., Rhizoctonia solani, Aspergillus flavus* *Species of Rhizoctonia, Pythium, Phytophthora, Fusarium, Didymella, Botrytis, Verticillium, Alternaria, Cladosporium, Helminthosporium, Penicillium* and *Plicaria*	Competition, direct antibiosis, induced resistance Toxin production
Purpureocillium lilacinum QLP 12 (previously Paecilomyces lilacinus)	*Verticillium dahliae, R. solani* and *nematodes*	Parasitism
Phlebiopsis gigantean *Pseudomonas* spp.	*Hetero basidionannosum* *Pythium* spp., *R. solani*	Competition for resources Production of antibiotics, siderophores, volatiles
Pythium oligandrum	Species of *Alternaria, Botrytis, Fusarium, Gaeumannomyces, Ophistoma, Phoma, Pseudocercosporella, Pythium, Sclerotinia* and *Sclerotium*	Hyperparasitism
Streptomyces spp.	Species of *Fusarium, Rhizoctonia, Phytophthora, Pythium, Phytomatotricum, Aphanomyces, Monosprascus, Armillaria, Sclerotinia, Verticillium, Geotrichum*	Mycoparasitism
Trichoderma spp. *(T. atroviride, T. asperellum, T. harzianum, T. viridae, T. gamsii and T. polysporum)*	Species of *Rhizoctonia, Fusarium, Alternaria* and *Colletotrichum* as well as c*omycetes,* such as *Pythium* and *Phytophthora*	Competition, resistance and hyperparasitism

Source: Panth et al., 2020

Preparation of talc based bioformulation of *Trichoderma / Pseudomonas*:

Material required:

Liquid medium (PDA broth/King,s B/ molasses etc.), fresh culture of *Trichoderma* and *Pseudomonas* , fermentor, talc powder, Carboxy methyl cellulose, large trays or blotting sheets , polythene bags etc.

Procedure:

1. Grow the *Trichoderma* in liquid medium for at least for 7-10 days and *Pseudomonas* for 72 hours for obtaining biomass either in flasks/glass bottles/in fermentor.
2. Mix fermentor biomass (15 kg), talc (30 kg) and carboxymethyl cellulose (300 gm) together and dry in shade.
3. Check the Cfu/ml or gm of formulation i.e. the inoculum culture of the antagonistic. It should contain a minimum population of 1x 10^8 cfu/ml or gm (For *Trichoderma*) and 9x10^8 cfu/ml or gm (for *Pseudomonas*) should be free from any kind of contamination.
4. Pack the dried formulation in polythene bags for its further distribution and use.

Future perspectives

Trends associated with the biological control of insects and diseases in greenhouses may be relevant.

The use of both conventional pesticides and biological control agents in Great Britain has been assessed since 1968 by the Ministry of Agriculture, Fisheries and Food. The use of biological agents increased from 17 ha in 1968 to 3,813ha in 1981 and to 30,889 ha in 1995 i.e. ten fold increase in the 14 years, primarily in insect biocontrol agents because no disease biocontrol agents were registered in the United Kingdom. However, most of the increase was recorded in protected greenhouse crops comprising 13,960 ha in edible crops and 7074 ha in ornamental greenhouse crops by 1995. Although protected crops represent a small fraction of the total area, but it accounted for two third of all biologicals. The use of insecticides in greenhouses has declined from 4866 ha in 1981 to 2292 ha in 1995. The area treated with insecticides in tomato declined from 2497 ha in 1976 to 324 ha in 1995, whereas the area treated with biologicals increased from 406 ha in 1976 to 10,350 ha in 1995 i.e., a 23-foldincrease. This increase may reflect multiple applications of biologicals, but the actual tomato area treated with biologicals increased from 20 to 77% in 1995. At the same time, the total production area of greenhouse tomatoes decreased by 83% from 1986 to 1995. It is evident that a combination of economic, political, and environmental factors has contributed to the transition to biologicals: loss of insecticide registrations, development of resistance to insects, and concern for workers' safety. Competition from field-grown produce from other countries has diminished the tomato greenhouse industry in UK, but growers used more intensive and integrated crop management systems than their predecessors to remain competitive. The exponential increase in the use of biological control of insects has become a crop management system and accordingly, the number of products has also increased. eg., in 1985, only four products were available—one bacterium, one fungus, and two predators, whereas, 16 biocontrol species were available after a decade. Greater availability may in turn have fostered the increase in biocontrol use. Did more companies in the market place create more demand for biologicals, or did the demand create more companies. Does this demand exist for biocontrol agents for greenhouse diseases only, and why are there not more biological disease control products in the market? We need to look at the present registration system and the greenhouse markets, and pose some basic ecological questions.

Conclusions:

The greenhouse industry is reacting to several drivers eg., efficient use of scarce water-supply and increased production through appropriate climate controls. Greenhouse production has grown exponentially in Spain and other countries may follow. This is highly relevant as the greenhouse environment provides unique opportunities for the management of pests through the characteristics similar to greenhouse production. The use of biological control agents has enhanced with the increase in size of the industry. The expenditure on biocontrol agents in greenhouses represented the majority of sales of commercial biological control agents globally.

Greenhouse production systems have adopted biological control and the industry is responding strongly to external influences to use pesticides which are enforcing the use of commercial biological control agents. Worker safety, paucity of registrations for use of pesticides within greenhouses, and consumers driving retailers to demand has led pesticide-free produce and an increase in utilization of biological control agents. The biological control industry in greenhouse production is strong and it is still growing. Hence, external drivers and internal support, may result in reduced pesticide use in greenhouses and biological control will become the cornerstone of pathogen management strategies, as has been believed in many greenhouse vegetable crops. With much research being conducted on these strategies in greenhouses, the use and efficacy of biological control is only set to continue to grow.

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6. ROLE OF BIOLOGICAL CONTROL AGENTS TO MANAGE DISEASES UNDER PROTECTED ENVIRONMENT

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Abstract: Protected cultivation of economically important crops facilitates the growers to fulfil the high market demands round the year while mitigating climatic extremes such as floods, droughts and other abnormalities. However, pests and diseases are a major constraint in crop production under controlled environment and commercial vegetable growers have relied on high dose of chemical pesticides for disease and pest control which resulted in adverse effects on environment, soil, water, animals and human health and development of resistant strains of pathogens. In this context, use of various ecologically sustainable pest management approaches becomes a compelled necessity. The microbial bio-pesticides have emerged as an important alternative and component of integrated pest management in disease management in an effort to conserve and sustain the diverse agro- ecosystem. Biological control agents (BCAs) offer several advantages *viz,* no residual effects and toxicity to plants, harmless to non-target organisms, cost-effective and usually self-sustained in soil. BCA's can modulate host immune system and enhance the root and plant growth by encouraging the beneficial soil microflora. Many potential BCAs viz. *Trichoderma* spp. (*T. harzianum, T. viride, T. asperellum, T. virens, T. hamatum, T. konningi etc.*) and *Gliocladium* have been utilized commercially against various soil borne pathogens viz. *Pythium, Phytophthora, Fusarium, Rhizoctonia, Sclerotinia sclerotiorum, Sclerotium* etc. BCAs like *Ampelomyces quisqualis* against powdery mildews. Bacterial antagonists *Pseudomonas fluorescens, Bacillus subtilis* and *B. amyloliquefaciens* etc. are effective against many soil borne diseases caused by fungi and bacteria. Recently, bacteriophages have emerged as potential bio-agents against bacterial wilt in solanaceous crops. In India, ICAR-IIHR has developed several bio-pesticide technologies which have been successfully demonstrated under open field and protected conditions for pest management in horticultural crops *viz.,* tomato, capsicum, English cucumber, rose, gerbera, carnation etc. The efficacy of commercial biopesticides like Arka Krishi Vriddhi, Arka Krishi Veera, Arka Krishi Samarakshak, Arka Krishi Rakshak, Arka Krishi Kawach, Seed-Pro and Arka Microbial Consortium have been validated at several locations in the country. The demand and consumption of bio pesticides is increasing and the gap in demand and supply may be attributed to the lack of large-scale production *i.e.*, mechanization and up scaling of production capacity, besides expensive registration procedures and lack of quality assurance and proper application technology.

Introduction

Indiscriminate and non-judicious use of chemical pesticides in agriculture has resulted in several adverse effects such as soil, environmental pollution, ecological imbalances, pesticide residues, soil and water contamination, destruction of natural enemies and beneficial bioagents, pesticide resistance, human and animal health hazards etc. The residue in food especially in fruits and vegetables as well as contamination of veterinary feed pose a greater challenge. Resurgence of pests due to failure of chemicals as the pests develop resistance to them over a period has made plant protection a costly affair.

It is the policy of the Government of India to encourage farmers to adopt ecologically sustainable pest management approaches rather than chemical pesticides. Therefore, Govt. of India has adopted Integrated Pest Management (IPM) as cardinal principle under the overall crop production programmes. The extension personnel and other stakeholders are being trained on the latest IPM technology and to adopt organic farming and bio-fertilizers. Use of microbial bio-pesticides in plant disease management is widely promoted, as a component of IPM, to conserve and sustain diverse Agro- ecosystem.

Biological control

Biological control is a method of plant disease management by inhibiting plant pathogens, improving plant immunity, and/or modifying the environment through the effects of beneficial microorganisms, compounds, or healthy cropping systems. The microbes that inhibit the growth, development, or reproduction of pathogens are called as antagonistic organisms. Antagonism frequently operates under natural conditions and it is difficult to manipulate due to the modifying effects of the environment. Hence, these antagonists are isolated and screened against target diseases and scaled up for mass production. The suppressive soil in which the pathogen cannot establish, develop, or survive are important for isolation of efficient antagonists for soil borne disease management.

Advantages of Biological control

Biological control offers many advantages over other approaches of plant disease management. BCAs are non phytotoxic, multiply easily in the soil and leave no residual problem. BCAs usually target a specific group of pathogens and therefore, have less negative impacts on the ecosystem as compared to fungicides. Many BCAs are self sustaining and maintain themselves for a longer time without additional efforts. They can modulate host immune system, allowing plants to allocate more energy and resources for agronomic traits important to the farmers. Biological control is cheaper than any other methods. Application of BCAs is safer to the environment and applicators, BCAs enhance the root and plant growth also by encouraging the beneficial soil microflora hence, results in increase of crop yield.

Mechanism of action of biological control agents against plant diseases

1. **Antibiosis:** Inhibition of pathogen through antibiotics produced by. streptomycin and penicillin are derived from antibacterial actinomycetes and fungus., respectively. Toxins like viridin, gleoviridin *etc.* are fungal antagonists against fungal pathogens
2. **Competition:** Two different organisms attempt to utilize the same limiting factors eg. nutrients, oxygen etc. where supply is not large enough to support both the antagonist and pathogen.
3. **Parasitism & predation**: Antagonist directly attacks the pathogen; *Trichoderma* coiling over pathogens eg. *Fusarium* sp. and *Rhizoctonia* sp.
4. **Induced systemic resistance:** Antagonists induce resistance systemically in host plants that provides protection against the invasion by the pathogen

Estimated demand and consumption of bio-pesticides in India

As per the estimates of Directorate of Plant Protection, Quarantine & Storage., GOI during the year 2020-21, as against demand of 11054 M.T. of technical Grade of bio pesticides there was production and consumption of 8645 M.T. only (Table 6.1). This gap in demand and supply may be attributed to lack of large-scale production *i.e*., mechanization and up scaling of production capacity, besides expensive registration procedures and lack of quality assurance and proper application technology. Over the five years perod from 2016-17 to 2020-21, gap in demand and supply varied between 18.48 to 31.18 per cent.

Table 6.1 Estimated demand and consumption of bio-pesticides in India

Year	Unit: M.T. Technical Grade				
	2016-17	2017-18	2018-19	2019-20	2020-21
Demand	10447	10409	9725	10852	11054
Consumption	7190	7174	7203	8847	8645
Demand supply gap (%)	31.18	31.08	25.93	18.48	21.79

Source: DPPQS, 2022

Potential bioagents used worldwide in disease management

There are many potential microbial biocontrol agents for disease management. Among them *Trichoderma* and *Gliocladium* have been utilized against wide range of pathogens. Many species of *Trichoderma* viz. *T. harzianum, T. viride, T. asperellum, T. virens, T. hamatum, T. konningi etc.* They have been very effective against the soil borne pathogens viz. *Pythium, Phytophthora, Fusarium, Rhizoctonia, Sclerotium* etc have been utilized commercially.

BCAs *Coniothyrium minitans* and *Sporidemium sclerotivorum* were effective against the sclerotia forming soil pathogens viz. *Sclerotinia sclerotiarum* and *S. rolfsii* with very wide range and prolonged survival for years in soil. The biotrophic powdery mildew pathogens can be managed with powdery mildew specific BCA viz. *Ampelomyces quisqualis*. The non-pathogenic fusaria specific to *Fusarium spp*. have been employed in many countries. Similarly, *Pythium nunn* was effectively utilized against damping off caused by *P. vexans* and *P. ultimum*. *Pseudomonas fluorescens* has been the most utilized bacterial antagonist against many soil borne diseases caused by fungi and bacteria. *B. subtilis* and *B. amyloliquefaciens* are other bacterial antagonists. *Agrobacterium tumefaciens* causes crown gall, a very deleterious disease in rose and many perennial crops, and *A. radiobacter* is very effective antagonist for this pathogen..*Talaromyces flavus* and non-toxin producing *Aspergillus niger* have also been identified against may fungal pathogens. *Streptomyces griseoviridis* belonging to actinobacteria is effective against many soil borne pathogens. Recently, bacteriophages are also emerging as potential BCAs against bacterial wilt in solanaceous crops.

Table 6.2 Important diseases under protected cultivation in vegetables and flower crops.

Disease	Symptoms	Predisposing factors
Powdery mildews	On the upper surface of the leaves, a fine white powdery fungal growth is observed. The infected areas show bright, yellowish spots on the other side of the leaves. The entire leaf blades turn brown and wither with the advancement of disease.	Cool and dry weather conditions favour the disease. It appears during the months of November–January and spread by air
Downy mildew	Angular yellow spots on the upper leaf surface and the corresponding undersides of such spots are covered with mouldy growth. Infected leaves wither and die.	Humid and cool conditions and frequent rains favour the disease. The disease appear during the months of October -January in extensive dew formation. Under protected cultivation downy mildew is not as severe as under open field cultivation.
Rust	Brown or white pustules are observed on leaf surface and severe infection leads to drying and defoliation of leaves	Cool and dry weather conditions favour the disease. The disease occurs during the months of November–January and spread by air.
Wilt	The fungal, and the bacterial wilt may be distinguished by yellowing and gradual wilt, and sudden drooping of plants in the afternoon, respectively	The disease can appear at any stage of crop growth. It spreads through irrigation water and contaminated garden tools and potting media.
Root knot nematodes	Yellowing of young leaves and stunting result in chlorosis. Root knots are produced on roots.	Under repeated monoculture in protected cultivation. Spread by infested soil, nursery and organic manures
Viruses	Leaves: mosaic, ring spots, interveinal chlorosis, curling and shoe string effects . Fruits, ring spots, rugged surface, malforming and distortion are observed	In naturally ventilated polyhouses, virus infection is severe during summer (March-June) under dry conditions due to increase in population of vectors. It is transmitted by sucking pests; whitefly, thrips, aphids and some viruses are mechanically transmitted.

Key considerations in use of biocontrol agents under protected cultivation

In protected cultivation, multiple disease and insect pest infestation occur in a particular space and time. In this situation, synergy in integration of biological agents for insect and disease control is required. Biocontrol registrations now require data on the interaction of pesticides with beneficial insects. The new BC products should be compatible with their current pest management strategies. In protected cultivation, there is intensive usage of fungicides hence, it is beneficial to use BCAs reported to be tolerant to pesticides. A novel formulation of carbendazim tolerant *T. harzinaum* has been developed at NBAIR, Bengaluru (erstwhile PDBC), which has been effectively utilized in IPM programmes under protected cultivation where carbendazim is extensively used to manage wilt disease in vegetables and flowers. The important fungal, bacterial, viral and nematode diseases infecting various crops under protected agriculture are depicted in Fig. 6.1-6.4.

Biological means of disease management in protected environment

1. Soil health test for nematodes and pathogens

Once fungal, bacterial or nematode plant pathogens establish in polyhouses, it is diificult to manage and needs huge efforts. Before starting protected cultivation, growers should approach nearby research institutes for assessment of the pest and pathogen load in soil. Susceptible crop should not be cultivated in sick soil.

2. Green manures and Crop rotation

IIHR recommends innovative interventions like cultivation of non-itchy type velvet bean (*Mucuna*) as a green manure crop to reduce soil borne inoculum of pests and pathogens (Fig. 6.5). It should be incorporated in soil at 50% flowering to reduce nematode infestation which is known to aggravate soil borne diseases also.

3. Nursery management

a. Nursery media enrichment: Grow own nursery or possess seedlings from reputed nursery. Raise the nursery under 40-60 mesh white nylon net until transplanting. Raise seedlings in pro-trays with cocopeat media. IIHR recommends use of Arka Fermented Coco-Peat. It requires less or no sterilization of the growth media, results in better germination and vigorous uniform seedlings. Seedling raised on this growth media attain early transplantation maturity. Alternatively, Coco Peat can be enriched with Arka Microbial Consortium (AMC) @ one Kg per 1000 Kg (1 tons) of Coco Peat (Fig. 6.6).

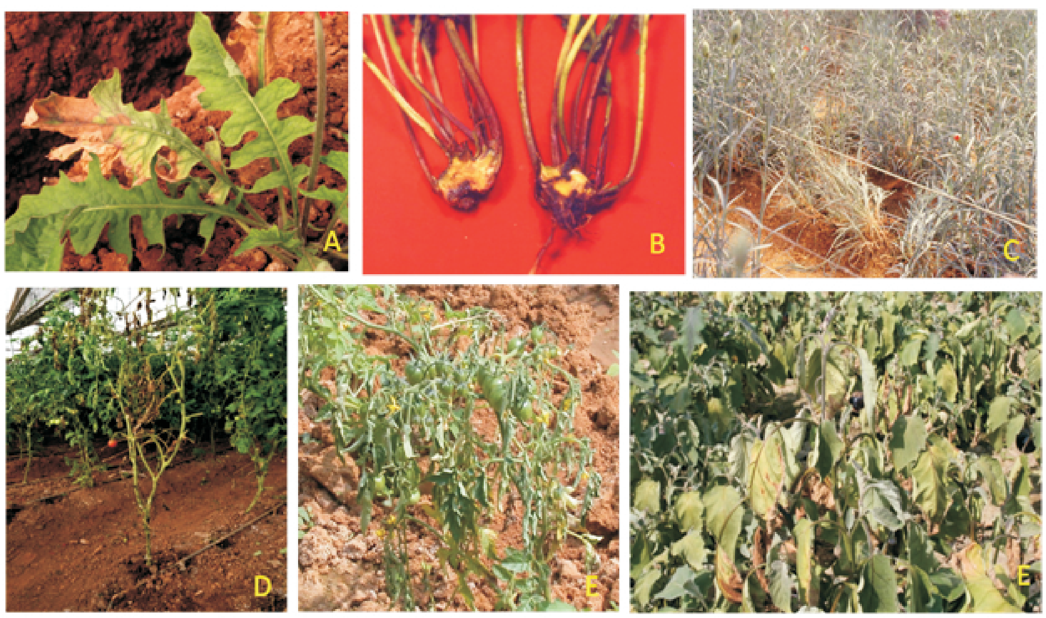
b. Seed treatment: Seed treatment or priming with microbial BCAs protect against seed and soil borne pathogens, promote root and shoot growth, leaf area, and seedling vigour and induces systemic resistance in plant against biotic and abiotic stresses throughout cropping period. Vegetable seeds should be treated @ 5-10g per kg of seed as seed coating. Spread seeds on the flour and sprinkle water on seeds, alternatively coat the seeds with equal volume of cool rice glue followed by sprinkling of bioagents and mix it well. Dry the treated seeds under shade before sowing. Talc formulation is used for the seed treatment depending on seed size

c. Seedling treatment: One week before transplanting, seedlings in nursery/portrays can be drenched with bioagents @ 20g per litre of water. Alternatively, seedlings can be dipped for10 minutes in liquid formulation of 10-20ml/l bioagents before transplanting.

d. Application of organic amendments: Application of organic amendments is a worldwide recommended strategy for the management of diseases caused by soil borne pathogens. Organic amendments may be used to promote the effect of added BCA's and/or beneficial soil microbiota to support natural suppressiveness of plant pathogens. Different complementary mechanisms have been proposed to explain the suppressive capacity of organic amendments, enhanced activities of antagonistic microbes, increased competition against pathogens for resources, release of toxic

Common diseases under protected cultivation.

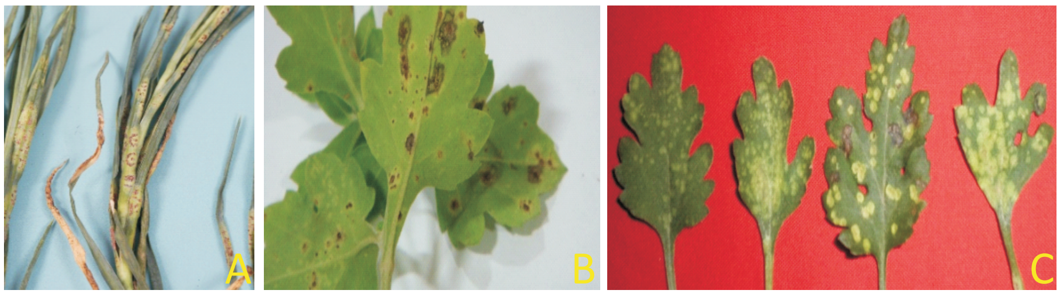
Damping of disease in nursery and seedlings



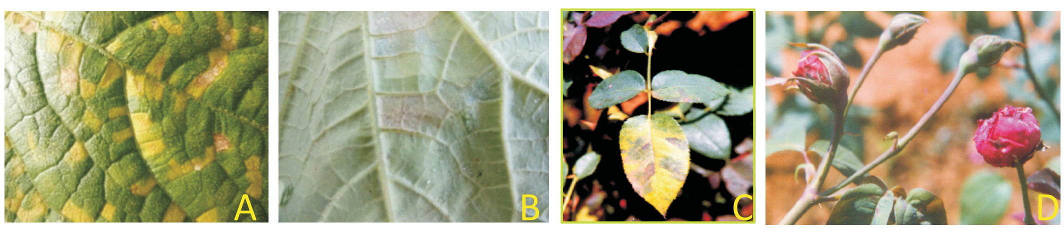
Wilts: A) Gerbera Fusarium wilt B) Gerbera Phytophthora wilt C) Carnation fusarium wilt D) Tomato Fusarium wilt E) Tomato bacterial wilt F) Brinjal verticillium wilt

Figure 6.1 Soil borne diseases of plants under protected cultivation

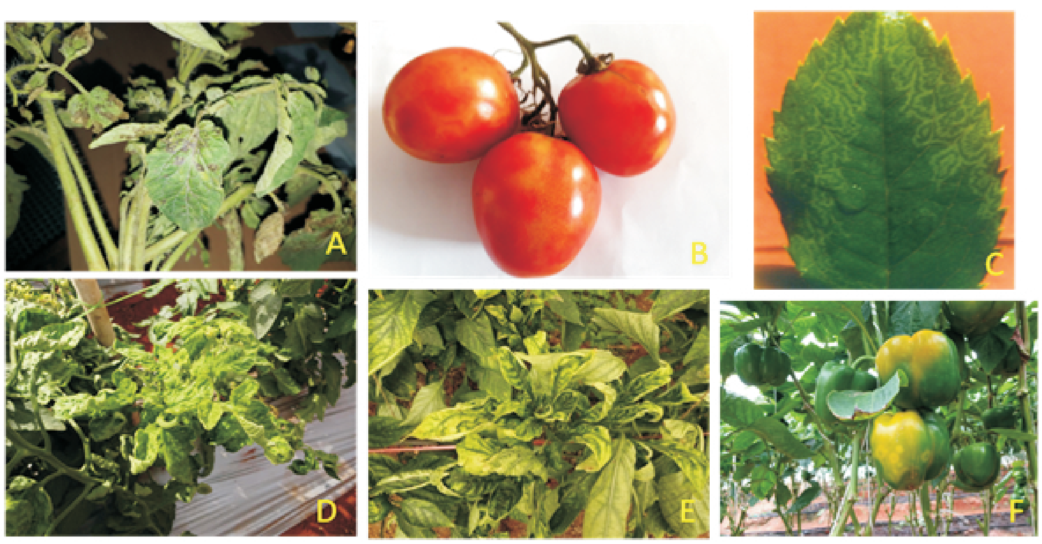
Powdery mildews: A Cucurbits B Capsicum C Tomato D Rose E Gerbera



Rusts: A Carnation B Brown rust of *Chrysanthemum* C White rust of *Chrysanthemum*



Downy mildew: A -B Cucurbits C-D Rose



Viruses: A-B GBNV in tomato, C Rose virus, D Tomato leaf curl , E Capsicum leaf curl
F Capsicum Tospo infected fruit

Figure 6.2 Foliar Diseases due to fungal pathogens and viruses in protected cultivation

Figure 6.3 Root knot nematode infestation A Cucumber B Crossandra

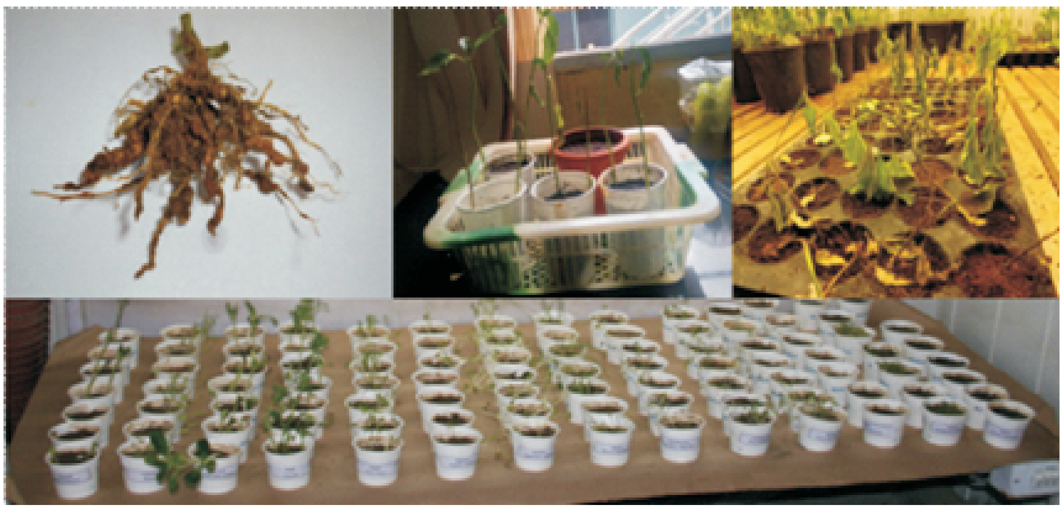


Figure 6.4 Root knot nematode population and soil borne pathogens assessment in soil

Figure 6.5 Crop rotation with (a) Mucuna and (b) Marigold to reduce nematode inoculum in soil

compounds during organic matter decomposition or induction of systemic resistance in the host plants. (Bonanomi *et al*., 2018; Rosskopf *et al,* 2020). At IIHR, application of organic amendments (OAs) has proved to be a successful strategy for management of soil borne plant pathogens and plant parasitic nematodes. Organic amendments are known to make soil suppressive by favouring multiplication and activity of beneficial microorganisms and applied bio-agents. IIHR recommends application of neem cake at the rate of 800kg per acre after its enrichment. It should be applied on cropping bed.

Different methods of application of biopesticides for management of soil borne diseases under protected cultivation

(I) Procedure for enrichment of organic substrates with microbial BCAs

Biopesticides like *Pseudomonas fluorescens* 1% W.P., *Paecilomyces lilacinus* 1% W.P and *Trichoderma harzianum* 1% W.P can be directly applied to the soil along with farmyard manure @ 12kg per acre. Instead of applying directly, FYM/Neem cake/vermicompost can be enriched with BCAs before applying in nursery and the main field. Enrichment reduces cost of inputs, ensures effective colonization and survival of bioagent in main field. Three different bioagents formulations, *Pseudomonas fluorescens* 1% W.P., *Paecilomyces lilacinus* 1%W.P and *Trichoderma harzianum* 1% W.P may be used for enrichment. Enrichment of organic substrates may be done as explained in Fig. 6.7 .

Enrichment of organic substrates with microbial biocontrol agents

1 kg of formulation of bioagents

If more than one bioagent is used (eg) *Trichoderma* and *Paecilomyces*, enrich the organic substrate separately and mix them at the time of application to soil

At the time of enrichment ensure that the organic substrate used is completely dry and in powder form

100 Kg
FYM / Powdered Neem Cake / Vermicompost

Cover with Coconut fronds or shade net or any other material to provide shade and leave it up to 15 days. Turn and mix on alternate day or every 2nd days and add water to maintain optimum moisture

Mix the enriched organic substrate and apply to soil along with remaining FYM

Enrichment should always be done in shaded place and excess moisture should be avoided in compost/ FYM/Neemcake during the enrichment period as excess moisture promotes growth of undesirable organisms.

Precautions to be taken during biocontrol agent application

1) BCAs need organic matter for multiplication and survival, always add bioagents along with sufficient FYM/Neem cake.
2) Soil organic matter could be increased by growing and incorporation of green manure crops like Sunhemp, Dhaincha or Mucuna.
3) Do not use fungicides as drench and spray after biocontrol agent application.
4) Do not store biopesticides along with chemical pesticides. Store biocontrol agents in cool, dry, shaded place.

Bio-pesticide products developed by IIHR for disease management in vegetables and flowers:

ICAR- IIHR has developed several bio-pesticide technologies that have been successfully demonstrated under open field and protected conditions for pest management at several locations of India. These eco-friendly technologies for sustainable management of pest problems in horticultural crops *viz.,* tomato, capsicum, English cucumber, rose, gerbera and carnation. At present, there are no bio-pesticides registered with label for exclusive use in protected cultivation. The following bio-pesticides developed at IIHR, Bengaluru can be used for pest management in protected cultivation as these have been validated in on farm demonstrations and frontline demonstrations by different extension agencies throughout the country.

1. ARKA Krishi Vriddhi

It is a Wettable powder (2×10^6 cfu/g) formulation of *Trichoderma harzianum* ICAR-IIHR Th-2 (NAIMCCSF-0033/ITCC 6888). It is recommended for use in brinjal, tomato, carrot and okra for managing root knot nematode (*Meloidogyne incognita*) and fungal pathogens; *Fusarium oxysporum* f. sp. *vasinfectum*, *Fusarium oxysporum* f. sp. *lycopersici*, *Sclerotium rolfsii* and *Fusarium solani* in these crops.

2. ARKA Krishi Veera

It is a wettable powder (2×10^6 cfu/g) formulation of *Trichoderma viride* ICAR-IIHR Tv-5 (NAIMCC-SF-0032/ITCC 6889). It is recommended for use in brinjal, tomato, carrot, okra and flowering plants against root knot nematode (*Meloidogyne incognita*) and fungal pathogens *Fusarium oxysporum* f. sp. *vasinfectum*, *Fusarium oxysporum* f. sp. *lycopersici*, *Sclerotium rolfsii* and *Fusarium solani*.

3. ARKA Krishi Samarakshak

It is a wettable powder (2×10^8 cfu/g) formulation of *Pseudomonas fluorescens* ICAR-IIHR Pf-2 (NAIMCCSB-0038/ITCC B0034). It is recommended for use in brinjal, tomato, carrot okra and flowers against root knot nematode (*Meloidogyne incognita*); bacterial pathogens *Ralstonia solanacearum* and *Erwinia carotovora;* fungal pathogens *Fusarium oxysporum* f. sp. *vasinfectum* and *Fusarium solani*.

4. ARKA Krishi Rakshak

It is a carrier-based formulation (2×10^6 cfu/g) of *Pochonia chlamydosporia* (=*Verticillium chlamydosporium*) IIHR- Vc-3 (NAIMCC-SF-0035/ITCC 6898). Its target pest is root knot nematode (*Meloidogyne incognita*) in brinjal, tomato, carrot and okra.

5. ARKA Krishi Kawach

It is a wettable powder (2×10^6 cfu/g) formulation of *Purpureocillium lilacinum* (=*Paecilomyces lilacinus*) IIHR- Pl-2 (NAIMCC-SF-0034/ITCC 6887). It is recommended for management of root knot nematode (*Meloidogyne incognita*) in brinjal, tomato, carrot and okra.

The BCAs ARKA Krishi Vriddhi, ARKA Krishi Veera, ARKA Krishi Samarakshak, ARKA Krishi

Figure 6.6 Model nursery with capsicum seedlings

Figure 6.7 Procedure for farm yard manure (FYM) enrichment with bio-pesticides

Rakshak and ARKA Krishi Kavach are applied as @20g/kg of seed, nursery bed treatment @50g/m^2 and 5kg/ha after enrichment in 5 tons FYM before transplanting or sowing.

6. Seed-pro

It is a microbial growth promoter and seed borne fungal disease suppressor. It is a seed coating formulation of *Bacillus subtilis* and *Trichoderma harzianum*. It Inhibits growth of seed borne and foliar pathogens. It promotes root and shoot growth, leaf area and seedling vigour index, induces systemic resistance against diseases (ISR). It is recommended as seed treatment @ 6-10g per kg seed in vegetable crops against seed borne fungi and foliar diseases.

7. Arka Microbial consortium

Arka Microbial consortium is a carrier based microbial product that contains N fixing, P & Zn solubilizing and plant growth promoting microbes in single carrier. Cocopeat enrichment @ 1 kg/1000kg helps in getting vigorous and healthy seedlings. It can also be applied as seed treatment @ 10-20g/100g seed.

In addition to it some of the bio-pesticides registered in India are given in Table 6.3

Other products being used in disease management under protected condition

1. Use of bio-stimulants

Spray application of bio-stimulants derived from organic sources enhances tolerance to diseases. Sagarika is an organic bio-stimulant derived from red and brown seaweeds. Red seaweed *(Kappaphycus alvarezii)*, enhances crop productivity and imparts resistance against stress. It can be applied as foliar spray @ 1-2 ml per litre of water as per the crop stage. Spray should be undertaken in the early morning hours after the evaporation of dew. Three sprays i.e. at plant establishment, pre - flowering and post flowering stages are required during the cropping period.

2. Waste decomposer

Waste decomposer, developed by National Centre for Organic Farming, is a consortium of microorganisms extracted from desi cow dung. It is sold to farmers in small bottles and can be used for mass multiplication. Mix 2 kg of jaggery in 200 litres of water in a container and stir well. Open the bottle and pour the contents of bottle into the solution (avoid direct contact of contents with hands). Stir the contents of the container and cover it with a paper/cardboard etc. and stir it once daily. The material will be ready within 4 days. The mass multiplied liquid waste decomposer culture, diluted with water in 1:3 proportion, can be applied as foliar spray for the management of bacterial, fungal and viral diseases effectively in different crops.

3. Preparation of Jeevamrutha solution

1. Ingredients: 10Kg fresh cow dung; 10 litres fresh cow urine; 2 kg horse gram flour, 2 kg jaggery and 1 kg native soil and 200 litres of water
2. Mix all the ingredients together in a plastic drum so as to dissolve in 200 litres of clean water.
3. Keep it inside the polyhouse or in safe and covered shaded place. Cover with lid or clean gunny bag.
4. Open the cover and keep the solution stir 3-4 times in a day, by turning the solution with wooden stick in clockwise direction. Avoid use of metal container for preparation of Jeevamrutha.

Cover the drum again with gunny bag or lid.

After five days**,** Jeevamrutha solution can be mixed thoroughly. Take the solution in a plastic bucket and drench @ 50-100ml solution per plant, directly to the root zone. Before drenching with Jeevamrutha, moist the soil by irrigation However, care should be taken to avoid excessive usage, as it adds higher nitrogen leading to leathery growth of leaves and may cause reduced availability of trace of micro-nutrients to plants.

Other Bio-pesticides registered under the Insecticides Act, 1968 in India for use in vegetables, fruits and flowers

SN	Biopesticide	Crop and target disease
1	*Ampelomyces quisqualis* 2.0% WP	Okra (Bhindi) Powdery mildew (*Erysiphe cichoracearum*)
2	Neem oil based EC containing, Azadirachtin 0.03% (300 ppm)	Bhindi, Powdery mildew
3	*Pseudomonas fluorescens* 1.75% WP (T Stanes Pf-1 Strain Accession No. MTCC 5671)	Tomato, Early blight, seed treatment @5 g/kg seed)
4	*Bacillus subtilis* 1.50% L.F (T Stanes Bs-1 Strain MTCC 25072)	Banana Sigatoka (*Mycosphaerella musicola*) 5litre /ha (foliar spray) diluted in 750 litre/ha
5	*Pseudomonas fluorescens* 0.5% WP (TNAU Strain Accession No. ITCC BE 0005)	Tomato wilt (*Fusarium oxysporum*.) Seed Treatment: 10 gm/kg of seeds Soil Treatment: 2.5 kg /ha
6	*Pseudomonas fluorescens* 1.0% WP (IPL/PS-01 Accession No. MTCC5727)	Wilt (*Fusarium oxysporum*), damping off (*Pythium aphanidermatum*), root rot (*Rhizoctonia* spp.), seed treatment 5 gm/kg as soil treatment @2.5 kg/ha Seedling root dip treatment@10 g/l
7	*Trichoderma viride* 0.5% WP	Tomato wilt (*Fusarium oxysporum*), seed treatment @10 g/kg
8	*Trichoderma viride* 1.5% LF (Strain No. TV-1, Accession No. MTCC 5170)	Tomato wilt (*Fusarium oxysporum* f.sp. *lycopersici*) @5 ml/kg seed treatment + 5 ml/lit water seedling dip + 3000 ml/ha soil treatment with dilution in water- 500 liter/ha
9	*Trichoderma viride* 1.0% WP (IPL/VT/101)	Cauliflower Stalk rot (*Sclerotinia sclerotiorum*) Seed treatment @4 gm/kg seed, soil treatment @ 2.50 kg/ha
10	*Trichoderma viride* 1.0% WP (IPL/VT/101)	Brinjal root rot/ wilt/ damping off (*Rhizoctonia bataticola*, *Sclerotium rolfsii*, *Fusarium oxysporum*, *Rhizoctonia solani*). Seed treatment @5 gm/kg seeds: Nursery Treatment @250 g/ 50 litres for drenching in 400 m^2 area. Seedling root dip treatment: Mix 10 g/l for 15 minutes. Soil Treatment @2.5 kg/ha
11	*Trichoderma viride* 1.0% WP	Tomato wilt (*Fusarium oxysporum*), Damping off (*Pythium aphanidermatum*, *Rhizoctonia solani*), Seed Treatment @ 9 g/kg seed. Root zone application: Mix thoroughly 2.5 kg of the product in 150 kg of compost or farmyard manure and apply this mixture in the field after sowing/ transplanting of crops

Precautions to be taken while preparing and applying Jeevamrutha solution

1. Wash the drum, before mixing of the material ingredients. Prepare the solution in a clean drum using clean water to avoid any chemical or other residues in the drum.
2. Always use fresh and clean water, fresh cow urine and cow dung and other materials and good quality fresh bio-pesticides from known sources, while preparing the solution, to ensure good quality of Jeevamrutha solution.
3. Do not mix any other products and solutions with Jeevamrutha solution, so as to avoid the negative effect on the solution and to prevent toxicity or scorching on the plants.
4. Keep the solution under shade and do not expose it to direct sunlight.
5. Apply fresh Jeevamrutha solution every time and avoid storing the solution beyond 7 days.

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7. INTEGRATION OF SOIL SOLARIZATION WITH OTHER ECO-FRIENDLY APPROACHES FOR THE MANAGEMENT OF DISEASES IN VEGETABLE CROPS

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Abstract: Continuous threats of soil borne disease epidemics in crop production, high cost of chemical fungicides and development of fungicide resistance, climate change, increasing concerns regarding human environmental and soil health necessitate the use of integrated soil borne disease management strategies. Soil solarisation is a technique where, the solar radiations are harnessed by covering the moist soil with thin transparent polyethylene mulch to raise soil temperatures so that it may be lethal or sub-lethal to pathogens. Experiments conducted for the last 20 years indicated an increase of 7-15°C in mean maximum soil temperature in different locations and the method has been found effective against several soil-borne pathogens in different crops. Integration of soil solarization with soil amendments, biological control agents and mycorrhizal fungi further enhance its efficacy. In bio fumigation, soil solarization is done after amendment with the residues of *Brassica* crops which release isothiocyanates (ITCs) chemically similar to methyl isothiocyanate, the principal from the synthetic fumigant metam sodium. Soil solarization also results in improved growth in plants. The mechanism for explaining increased growth responses and yield in plants has been attributed to chemical factors (like release of nutrients and various growth factors and nullification of toxins) and biological factors (elimination of minor or unknown pathogens and stimulation of beneficial micro-organisms).

Introduction

Soilborne diseases are among the most destructive factors in crop production. Many vegetable and high-value crops and ornamentals are vulnerable to the wide range of disease-causing organisms which may either reduce the yield, aesthetics, marketability etc. The phase-out of many chemicals and rising awareness towards resistance development, soil, water, human and environmental health, and climate change necessitates the quest for alternative suitable management options. Many non-chemical options such as sanitation, legal methods, resistant cultivars/varieties, grafting, cropping system, soil solarization, biofumigants, soil amendments, anaerobic soil disinfestation, soil steam sterilization, soil fertility and plant nutrients, soilless culture and biological control methods may prove costly and inefficient individually . However, soilborne plant pathogens can be managed below the economic threshold level when these methods are applied as a system approach. Soil solarization is a technique where, the solar radiation is harnessed by covering the moist soil with thin transparent polyethylene mulch to raise its temperatures for heating the soil so that it may be lethal or sub-lethal to pathogens.

Principles of solar heating

Soil solarization involves the use of thin transparent polyethylene mulch for covering the soil surface to capture solar energy for heating the soil. The heat generated in the soil due to increase in soil temperature acts as a lethal agent in controlling or inactivating soil-borne pathogens in the soil. On an average, one square centimeter area outside the earth's atmosphere and parallel to its surface receives 2 colories/cm^2/minute of energy in the form of solar radiation but only half of it finally reaches the ground. The energy is lost from the soil in the form of long wave radiations, through conduction, convection and water evaporation. Absorption of solar radiation varies according to the colour, moisture and texture of the soil. In general, the soil has a relatively high thermal capacity and is a poor heat conductor. Transparent polyethylene mulch should be used since, it transmits most of the solar radiations that heats the soil. Studies carried out in different countries showed that soil solarization with transparent polyethylene mulch resulted in increase in soil temperature to different levels. In Israel, during the month of July-August, the recorded soil temperatures of mulched soil at depths of 5 and 20 cm were 45 and 55°C, respectively.

Mechanism of disease control

Solarization affects the inoculum of pathogens existing in the soil by:

a) reducing inoculum density through microbial killing of the pathogens, already weakened by sub-lethal heat; partial or complete annulment of fungistasis and subsequent lysis of the germinating propagules;
b) parasitism or lysis by stimulated antagonists
c) reduction of inoculum potential due to competition or antibiosis induced by solarization; and
d) diminishing competitive saprophytic ability of the pathogen, in the absence of the host, due to antibiosis or competition. Solarization also induces effect on the host due to cross protection. Integration of solarization with other means such as organic amendments or biocontrol agents improves disease management as the heating weakens a pathogen and even reduced dosages of various agents might suffice for improved control combining with biocontrol agents, organic amendments etc.

The physical effect of soil solarization is exerted on the soil-borne pathogens when they are subjected to moist heat, at temperatures exceeding the maximum required for the growth hence, their viability is reduced. The thermal death rate of an organism depends on both the temperature level and the exposure time, which are inversely related. The success of soil solarization is based on the fact that most plant pathogens and pests are mesophilic or unable to survive for long periods above 37°C. The heat sensitivity of these organisms is related to an upper limit in the flaccidity of cell membranes which lose their ability to function at high temperatures. Other causes of death of organisms at high temperatures involve the sustained inactivation of enzyme system, especially respiratory enzymes. In practice, populations of soil-borne fungal pathogens is greatly reduced at temperatures of 40-50°C with exposure time ranging from minutes to hours for the higher temperatures and up to days for the lower ones. However, combining solarization with soil amendments, biological control agents, reduced doses of pesticides and other methods of disease management may reduce the duration of mulching.

Integration of soil solarization with other methods, bio-fumigation

Bio-fumigation is another disinfestation method and refers to the suppression of soil borne pathogens or pests by decomposing organic materials, such as agricultural by products or manure. Bio-fumigation is primarily the use of residues of Brassica crops as soil amendment which release isothiocyanates (ITCs), chemically similar to methyl isothiocyanate, the active agent from which the synthetic fumigant metam sodium was derived or synthesised. Fermentation of residues of *Brassica* crops and other organic materials release volatile compounds that mostly have a fumigant action against plant pathogens. Combination of soil solarization and bio fumigation is known as bio-solarization and it is more effective particularly in places where, the maximum temperature do not reach the lethal level. Using soil solarization in combination with soil fumigants or with certain crop residues greatly shortens the time needed to control pathogens and pests. Further, this also extends the use of solarization to regions which are considered to be marginal because of air temperatures, length of day, and intensity of sunlight. *Brassica* species contain glucosinolates and their degradation products have potential use as fumigants. Glucosinolates,on hydrolysis by the enzyme myrosinase, produce D-glucose, sulfate, isothiocyanates (volatile mustard oils), thiocyanates and nitriles. Isothiocyanates (ITC) and nitriles have been demonstrated to control fungi, bacteria etc. Allyl isothiocyanate (AITC) is the predominant ITC produced by Indian mustard (*B. juncea*). There are numerous reports which corroborate the effectiveness of this technique. Soil solarization in combination with soil amendments, crucifer residue and microbial pesticides like *Trichoderma* spp., *Gliocladium* sp., *Pseudomonas* sp. has also been reported to be effective in strawberry, gladiolus, vegetables and other crops against different soil-borne diseases. However, if applied as an integrated measure, combining the plants having allelopathic effect (*Brassica* cover crops and *Allium* species), the efficacy of soil solarization can be increased.

Organic amendments of the soil are traditionally used to improve soil conditions and crop productivity. Additionally, these can also aid in suppressing soilborne pathogens. Efficacy of organic amendments may be improved by integrating it with various other means eg., bio-fortification, soil solarization etc. Biofortification of organic compost with beneficial microorganisms can enhance the disease suppressiveness of the soil with more efficacy and reliability. The addition of organic amendments followed by soil solarization can increase beneficial microbe interaction in the soil with induced resistance in the host plant. Thus, balanced use of soil organic amendments along with the other methods such as soil solarization, biological antagonists can be an integrated approach for the management of soilborne pathogens.

Disease management

Field experiments have been carried out, since 1974, in different parts of the world for evaluating the effectiveness of soil solarization in disease management. The method was applied against various soil-borne pathogens, responsible for causing wilt, collar rot and root rot diseases in various crop plants. These pathogens multiply faster in soil due to repeated cultivation of a crop and are more difficult to control. In general, soil solarization was found effective against several soil-borne pathogens under different agro-climatic zones. The technique of soil solarization has now been evaluated, modified and refined under local conditions in more than 50 countries, including the United States, Israel, Greece, Morocco, Japan, Italy, Jordan, United Kingdom, England and India.

Soil solarization was found effective against the wilt pathogen *Verticillium dahlia* and it resulted in reduction in disease incidence by 65 and 95 per cent, in tomatoes and potatoes respectively, whereas, incidence of pink root (*Pyrenochaeta terrestris*) in onion was reduced by 90 per cent. It is evident that the efficiency of soil solarization varies with soil-borne pathogens infecting different hosts.

Increased growth response

The mechanism for increased growth responses and yield in plants has been attributed to chemical factors (release of nutrients and other growth factors, nullification of toxins etc.) and biological factors (elimination of minor or unknown pathogens and stimulation of beneficial micro-organisms). Soil micro-organisms, beneficial to plant growth e.g. *Bacillus* spp., actinomycetes are not or least affected by soil solarization than are the pathogenic organism whereas, other beneficial microorganisms e.g. fluorescent pseudomonads may quickly recolonize the treated soil . Heating causes the release of soluble mineral nutrients from soil organic matter and heat killed soil biota and induces the upward movement of mineral nutrients in the soil profile. Disease reduction in solarized soils was usually accompanied by an increase in yield and other growth parameters, and beneficial organisms to variable extents.

Other benefits

Induced resistance can be demonstrated in some foliar diseases even if the site of treatment, eg. the roots surrounded by solarized or *Trichoderma*-treated soil, is different from the site of infection on the leaves. A number of studies showed the reduced sensitivity to foliar diseases in plants grown in solarized soil, despite the fact that only the roots are in contact with the treated soil. In addition, solarization frequently stimulates rhizobacteria, such as fluorescent pseudomonads and *Bacillus* spp. which are potential inducers of resistance which may contribute indirectly to induced resistance in the plants grown in solarized soil. Despite certain similarities in the plants' responses to soil solarization and *T. harzianum* with respect to induced resistance, it is not yet known whether the resistance-induction mechanism is identical in the two systems. The studies on resistance induced by soil solarization and *T. harzianum* demonstrate the involvement of control mechanisms in addition to the direct detrimental effect on the pathogen.

Besides, a general recommendation for using a system-based approach based on current research would be the integrated use of different methods explained above. For example, soil solarization to manage different soilborne diseases as a pre-planting measure followed by the use of clean seed materials to reduce the chance of introduction of primary inoculum; use of *Brassica* cover crops as a natural source of biofumigants in coherence with crop rotation may reduce the chance of pathogen build up due to monoculture; and introduction of biocontrol agents to the ecosystem.

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8. PLANT BENEFICIAL MICROBIOME: FUNCTIONAL CHARACTERIZATION AND POTENTIALITIES IN SUSTAINABLE DISEASE MANAGEMENT

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Abstract: Plant pathogens cause approximately 10-20% yield losses in major crops worldwide in spite of the adoption of protection. Using available natural resources including plant beneficial microbiota is one of the potential and promising alternatives for sustainable disease management as the plant and their associated microbiota are co-evolving simultaneously for millions of years. This co-association of microbes and plants has numerous benefits to plants including nutrient acquisition, fight against abiotic stresses and disease suppression. The plant-microbiota members include neutral, pathogenic, and beneficial organisms during their life span. Microbiome studies have provided important functional attributes of plant microbiota and opportunities which can lead to better crop management, especially under biotic threat due to fungal, bacterial, viral and nematode invasions. However, successful deployment of microbiota-mediated crop protection will largely depend on the mechanistic understanding of the way microorganisms interact with their hosts and with one another in natural environments to regulate the plant disease triangle. Extensive research is being done on plant microbiome exploration with the aim to dissect the specificity, diversity and function of complex microbial communities associated directly or indirectly with the plant (i.e., endophytic, epiphytic, and rhizospheric communities) including the translation of molecular understanding of plant microbiome research to enhance resilience in the dynamics of emerging and re-emerging plant diseases. Several microbiome engineering strategies *viz.*, soil conditioning, artificial microbial consortia and host-dependent microbiome engineering have proved useful in strengthening the disease resistance and nutrient acquisition in host plants. Integrated approaches of experimental biology, multi-omics, and computational biology have offered valuable quantitative insights into plant–microbiome interactions and the underlying mechanisms. Moreover, plant-oriented signalling molecules such as salicylic acid and various metabolites in root exudates, strongly affect the dynamics and composition of microbiome, inferring that plant microbiomes can be artificially modulated using such microbe-stimulating chemicals in an efficient and precise manner. It is speculated that deep understanding of the dynamics of plant–microbiome–environment interplay has the potential to lay strong foundation for the deployment of engineered microbial consortia for sustainable and improved plant production under a continuously fluctuating environment. It will certainly boost microbiome-mediated smart agriculture system for enhanced crop productivity and environmental sustainability.

Introduction:

The global demand for food will increase by 70% in 2050, while, the farmer will have to face adverse climatic conditions in the form of nutritionally depleted and contaminated soils, and water scarcity. In this context, using available natural resources including plant microbiomes, is the most sustainable alternative (Santos and Olivares, 2021)**.** The plant microbiome i.e., phytomicrobiome, plays an important role in plant health and productivity and has received significant attention (Song et al. 2020). Microbiome is defined as the set of genes in the organisms that colonize a given environment. The term 'microbiome' was first coined by Lederberg and McCray (2001) as "the ecological community of commensal, symbiont or pathogenic micro-organisms and were employed with reference to the microorganisms associated with human beings". Currently, the term microbiome encompasses microorganisms in any configuration and include plant system also. The microbial component of the plant halobiont, termed as plant microbiota (comprising all microorganisms) or the plant microbiome (comprising all microbial genomes) has important functions in supporting plant growth and health. Depending upon the specific habitat, plants' microbial communities are classified as rhizo-, phyllo-, and endo-spheric regions. It has been observed that plant-associated microbiomes confer various fitness advantages to the host plant, including growth promotion, nutrient uptake, stress tolerance and resistance to pathogens (Srivastava et al., 2021; Gupta et al., 2021). The assembly of plant microbiota is basically the result of a hierarchy of events that can generate the establishment of stable and diversified microbial consortia based in cooperative interactions. Fig. 1 depicts several types of factors, e.g., environment and interaction amongst microorganisms (competition and cooperation) and between host and microorganism, which become modulators in the assembly of the microbial communities associated with the plants, promoting diversity and microbial co-occurrence and ultimately determining the fate of a pathogen invasion in causing a disease. Briefly, plants are able to influence soil microbial communities leading to microbial-mediated protection in two distinct protective microbiological layers, i.e., rhizosphere (first line of microbiological defense) and endosphere (second line of microbiological defense) to fend off the pathogen infection. The host genetic background can shape distinct microbial communities' structures in the rhizosphere. The environment is able to affect plant growth, microbial communities, and pathogen infection. The success of pathogen infection is determined by the interactions with the surrounding environment, plant-associated microbiome, and complex nature of below ground interactions (Fig. 8.1).

There are two main approaches to achieve this synthetic biology-based plant microbiome engineering i.e. bottom up and top down.
A) Bottom-up approach: The bottom up microbiome engineering approach starts with the isolation and screening of specific plant-associated microbe strains. Selected strains could then be engineered to carry or express desirable traits that support plant growth and/or survival. These engineered microbe strains are then reintroduced into the phtyobiome for their specific roles to play.
B) Top-down approach: The top down approach initiates from the desired trait. In this case, a host is not engineered into a specific microbial strain, but it is introduced into the phytobiome via mobile genetic elements or phage delivery systems that can 'infect' various microbes. Hence, the trait can be introduced into several different strains of microbes. It also takes advantage of the genetically promiscuous nature of many microbes, which may share genetic material easily and freely with each other through a process known as horizontal gene transfer.
Irrespective of the chosen approach, plant microbiome engineering has several potential applications e.g. to learn more about the plant microbiome, which in turn will increase the fine-grained engineering potential. Depending on the traits expressed by the engineered microbiomes, they may be utilized in pest control, bio- fertilization, and bio stimulation (for example, by synthesizing extra plant growth hormones).

Approaches for studying structure and function of plant microbiome
Traditional microbiology involves isolating and culturing microbes from an environment using organism specific different nutrient media and growth conditions. Pure culture of an organism is required to study its genetics and physiology, but culture-dependent techniques miss the vast majority of microbial diversity in an environment. Several culture-independent, molecular techniques are used in microbial ecology e.g. PCR amplification of the ubiquitous 16S ribosomal RNA (rRNA) gene of prokaryotes (Compant et al., 2019). Sequencing the variable regions of this gene allows precise (species- and strain-level) taxonomic identification. High-throughput sequencing technologies have been widely adopted for identification of thousands to millions of sequences in a sample, revealing the abundance of rare microbial species. Eukaryotic microbes eg. fungi the hypervariable internally transcribed spacer is often used to study the taxonomic discrimination. Recently, a great advancement has been achieved in culture independent techniques for analyzing plant microflora by direct cloning of environmental DNA. Several molecular techniques e.g., terminal restriction /restriction fragment length polymorphism (T-RFLP/RFLP), single strand conformation polymorphism (SSCP), denaturing/temperature gradient gel electrophoresis (DGGE/TGGE), fatty acid methyl esters (FAME) and next generation sequencing (NGS) technology have been used to study plant microbiome communities. In addition omics techniques, such as meta-transcriptomics, meta-proteomics, metabolomics, or even single-cell genomics can also support the development of new enzymes/proteins, using recombinant DNA technology and metabolic engineering. The advancement of these modern culture-independent techniques have substantially been applied in diverse microbial diversity studies for genetic data based microbial distribution (metagenomics) without disrupting the

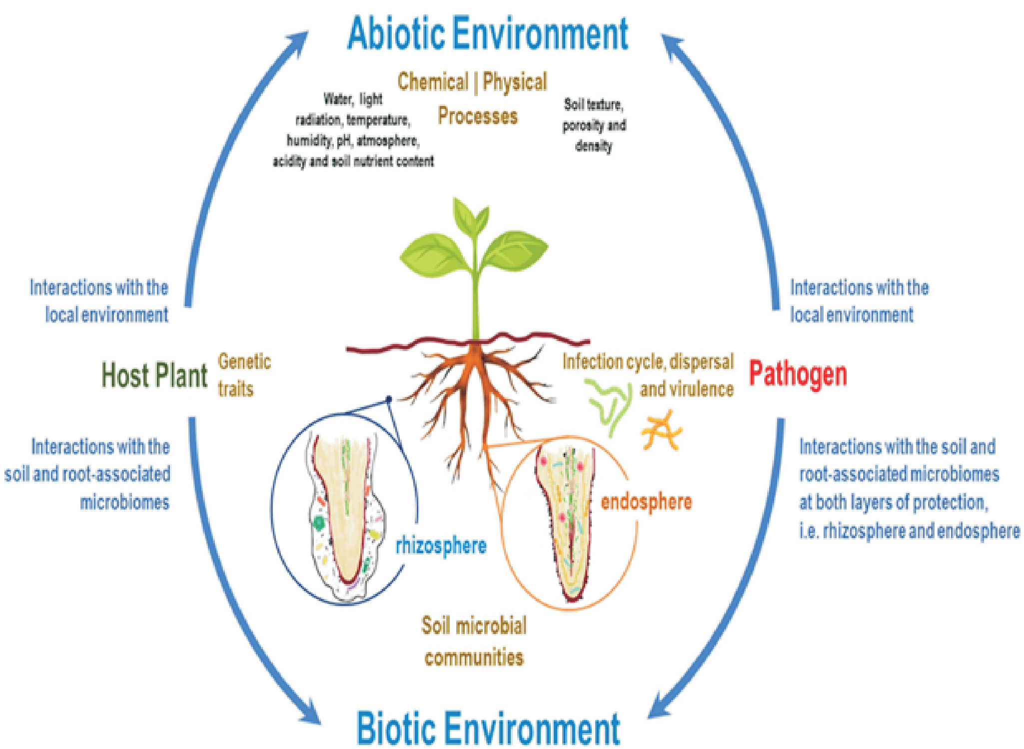

Figure 8.1Microbial-mediated protection and complex interactions and drivers affecting plant *health in nature*

texture of ecosystem. The schematic representation of diverse approaches and methodology of culture-independent techniques for assessing microbial communities associated with a targeted host plant is shown in Fig. 8.2. Preparation of a metagenomics library is very important to obtain consistent metagenomics data, which may be selected for secondary metabolites and enzymes profiling. The quantitative PCR (qPCR) using microbial DNA extracted from plant samples as template has a great potential to assess diversity in microflora populations. The gene based identification of 16S/18S rRNA (ribosomal RNA) are target molecular markers for assessing the diversity, richness, evenness, and structure of microbial communities. Several technological innovations viz., molecular fingerprint methods involving cloning and sequencing of PCR amplicons have been used to access the structure of a target microbial community. These approaches are being facilitated by the advancements in NGS leading to the generation of huge quantity of nucleotide sequences. Advancements in sequencing technologies along with bioinformatics intervention using appropriate softwares for analysis, have expedited the structural and functional assessment of miocrobiome associated with a plant.

Functions of microbiome in plant health

Generally, specific characters or attributes displayed by an individual microbial group in the microbiome is of significant importance with respect to plant health, and it is influenced by variety of factors including microbial diversity, environmental factors, and host plant species (Gao et al., 2021; de Faria et al., 2021). The microorganisms offer several direct health-related benefits to their host plants including nutrient acquisition, mitigation of environmental stresses, and protection from pathogens. Beneficial microbes protect plants from pathogen attacks either directly (by interacting with pathogens) or indirectly (by activating the innate immune responses of the host plants).

Microbiome meditated direct suppression of plant pathogens

The plant-microbiota members include neutral, pathogenic, and beneficial organisms during their lifespan. Plants establish beneficial associations with microbial communities and tend to cope with the infections caused by diverse pathogenic microorganisms. Soil-borne pathogens *viz*., *Rhizoctonia solani*, *Fusarium oxysporum*, *Verticillium* spp., and *Fusarium solani* etc. cause diseases on numerous plant species, including economically important crops, leading to significant qualitative and quantitative economic losses. These pathogens can survive in soil for long periods of time through hard resting structures i.e. chlamydospores, melanized mycelia, oospores, cysts, sclerotia etc., until they sense life signals from their corresponding host plants. It is evident from the fact that free amino acids, phenolic compounds, and sugars in root exudates of watermelon and tomato significantly enhanced the sporulation and spore germination of *F. oxysporum*. The infection of soil-borne pathogens usually causes inhibition of root development, root rot, stunted growth, stem or collar rot, wilting, and damping-off of seedlings. Some soil-borne pathogens infect a wide range of host plants rendering traditional control measures ineffective. Same groups of soil-inhabiting bacteria negatively regulate the plant health, e.g., *Agrobacterium tumefaciens*, the causal agent of crown gall disease, and *Ralstonia solanacearum*, causing bacterial wilt.

Pathogens must interact with the complex microbial community of rhizosphere to develop an intense pathogenic impact on plants. Pathogens negatively affect the plant health by interacting with beneficial microbiota, i.e., by competing for nutrients and space, and the production of antimicrobial compounds. Pathogens also promote colonization of harmful microbes by delivering effector proteins that cease the activities of beneficial microbes in rhizosphere community. Plants and their associated microbiota are co-evolving simultaneously for millions of years. This co-association of microbes with plants provides many benefits to plants including nutrient acquisition, fight against abiotic stresses, and disease suppression. Host-linked communities of beneficial microbes are involved in disease suppression and nutrient mobilization in plants, e.g., *Pseudomonas* spp. can reduce the growth of plant pathogens through competition and antibiosis. However, the overall disease suppression in soil is affected by various factors, i.e., genetic background of hosts and pathogens, population dynamics of pathogens, diversity and composition of plant microbiota and biotic and abiotic conditions. The disease suppression ability is associated with synergistic efforts of microbes rather than individual specific efforts. Some simple mechanisms, i.e., production of antimicrobial metabolites and volatile substances in antagonistic bacteria improved the efficacies of the disease-suppressive soils. Among the mechanisms of disease suppressive soils, antibiosis (i.e., production of antimicrobial metabolites by an organism to suppress the growth and proliferation of another organism) has been widely studied and antibiotics such as 2,4-diacetylphloroglucinol (DAPG) and phenazines (PHZ) reported to have potential roles in plant disease suppression. In case a pathogen is able to surpass the rhizo-or phyllo-biome (i.e. the first line of defense against invading pathogens), enters the plant and then endophytes become activated to provide an extra layer of protection to plants. The endophytes start recruiting microbial communities, which initiate their genetic machineries to produce defensive enzymes and metabolites against pathogens. *Fusarium* wilt disease in various crops (e.g., tomato, lettuce, and cucumber) was suppressed when these crop plants were grown in disease suppressive soils enriched with bacterial phyla, Acineto bacteria and Firmicutes. General or specific disease suppression can be achieved by modulating the composition of microbial communities through different management practices, e.g. crop rotation, green mannuring and compost addition. Plant-associated microbes are potential antagonists which can resist phyto-pathogens. These microbiomes interact directly with pathogens and inhibit their growth and niche overlap with microbes for resource competition is also a major factor in stimulating biocontrol activity.

Microbiome and its roles in activation of plant immune response

The beneficial features of plant-associated microbes can boost the immune responses in plants against biotic/abiotic environmental constraints. Microbiomes help their host plants to acquire resistance against pathogens via modulation of plant defense mechanisms (Song et al., 2020). The microbe-triggered immune response makes plants resilient against pathogen attack and boosts their disease combating efficiency. Microbiomes can reinforce the defensive capabilities of plants by interrupting the plant-pathogen interactions, which subsequently improve the disease resilience in plants. For instance, bacterial antagonists belonging to genera A*chromobacter*, *Comamonas*, *Curtobacterium*, *Enterobacter*, *Leclercia*, *Microbacterium*, *Pantoea*, *Sphingobacterium*, and *Stenotrophomonas* showed tremendous biocontrol potential against *Magnaporthe oryzae* and triggered the expression of defense genes (*OsCEBiP*, *OsCERK1*, *OsEDS1*, and *OsPAD4*), against blast in rice seedlings. Similarly, root-associated bacteria, *Pseudomonas* sp. EA105 and *Pantoea* sp. EA106 induced disease suppression in *M. oryzae* challenged rice plants by triggering jasmonate- and ethylene-dependent induced systemic resistance (ISR) responses. Pathogen attacks induce changes in the root exudation pattern of host plants, which can result in the colonization of specific resistance-inducing microbiota. Diverse microbial populations inhabiting the episphere and endosphere are involved in the activation of defense machinery of tomato plants against *F. oxysporum* attack by inducing cell wall fortification through the modulation of salicylic acid biosynthesis pathway. Similarly, the root-associated microbiome induced resistance in strawberry plants was observed against two soil-inhabiting fungal pathogens, *Verticillium dahliae* and *Macrophomina phaseolina*, in controlled field trials. However, environmental conditions and soil health play important roles in the development of such beneficial plant–microbe interactions.

Alterations in the composition of root exudates may manipulate root microbiomes, and activate and enhance plant-beneficial microbial groups in the rhizosphere. Microbiome-induced resistance has been reported for various diseases in different plant species, e.g., potato scab, sugar beet *Rhizoctonia* damping-off, *Fusarium* wilt, and wheat take-all. Selective enrichment of microbial groups is responsible for the induction of immune responses in plants against biotic and abiotic stresses, and this induced immunity can be transmitted over generations. However, ISR-inducing microbes need to bypass the plant immune system to develop a symbiotic relationship with their host plants. Beneficial microbes employ mechanisms similar to pathogens which suppress activities of plant immune responses. For example, *Rhizophagus intraradices*, an ISR-inducing arbuscular mycorrhizal (AM) fungus, suppresses plant immune responses and promotes its root colonization by producing SP7 *effector*. Likewise, *Laccaria bicolor*, a symbiotic ectomycorrhizal fungus, colonizes plant tissues by suppressing salicylic acid-mediated immune responses through MiSSP7 effector. Moreover, compromised immune responses have also been reported in *A. thaliana* after colonization by *Trichoderma*, *Bacillus subtilis*, and *Pseudomonas fluorescens* WCS417r. In addition to down

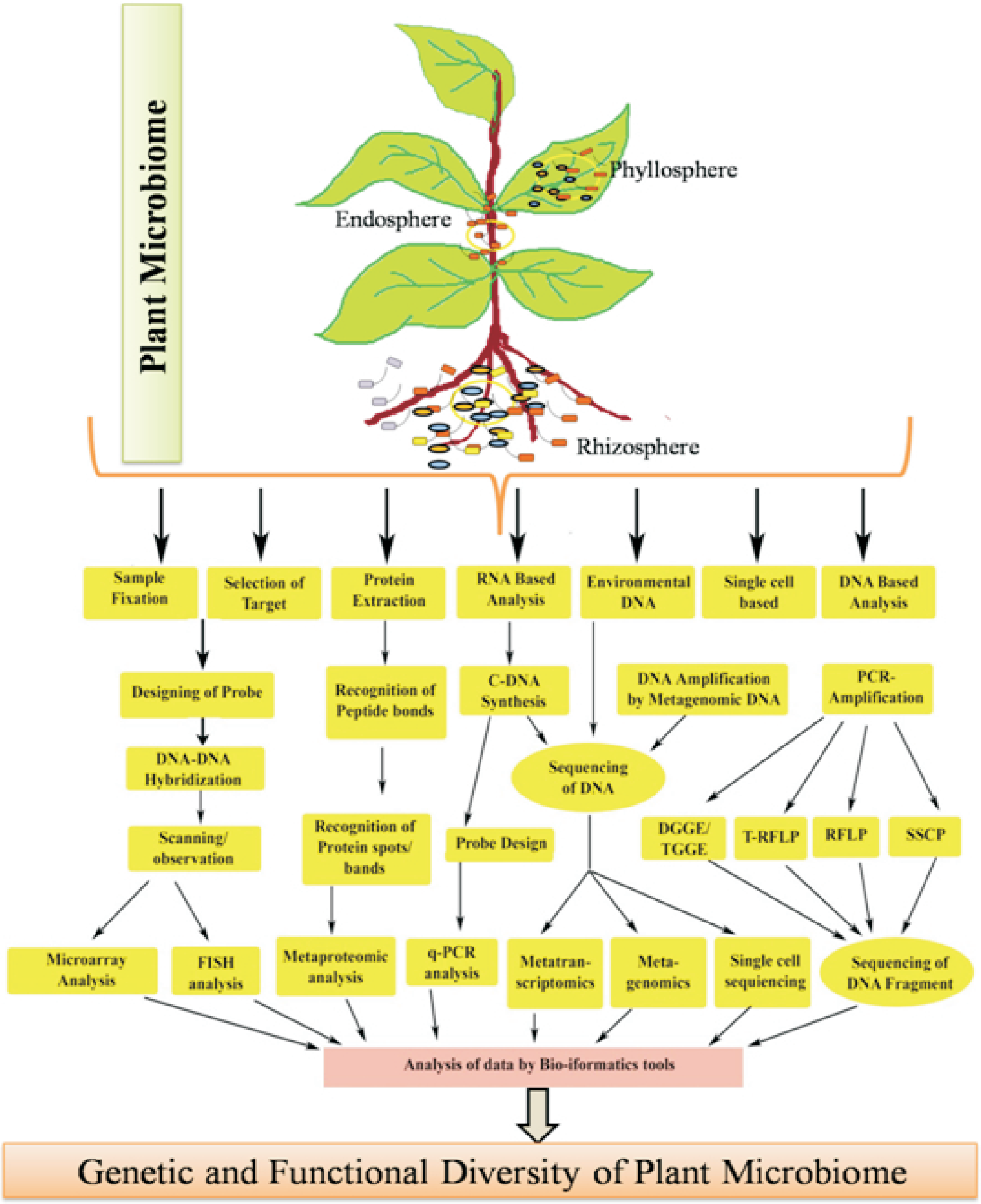

Figure 8.2Approaches for studying the plant microbiome

regulating local immune responses to facilitate colonization, plant-beneficial microbes also produce elicitors/signals to activate systemic immune responses. The beneficial services provided by the microbiome to pathogen-challenged plants are presented in Fig. 8.3. Briefly, in plants, pathogen-oriented molecular patterns (i.e., PAMPs) or plant-beneficial bacteria activate induced systemic resistance (ISR). Positive interactions between plant and microbiome help plants in combating diseases and other environmental stresses, for boosting growth and biomass production. Beneficial plant-microbiota competes with phytopathogens for colonization, resources, and habitat, etc. The beneficial microbes, directly suppress the proliferation of pathogens and the symptom expression in plants through numerous mechanisms, i.e. antibiosis, toxin production and nutrient sequestration.

Microbiome Engineering and its functional benefits on plant health
Several emerging microbiome engineering strategies (Fig 8.4), such as soil conditioning, artificial microbial consortia, and host-dependent microbiome engineering, have been reported to strengthen the stress tolerance, disease resistance, and nutrient acquisition in host plants (Noman et al., 2021; Kaul et al., 2021).

Strategy 1: ***Traditional soil conditioning using organic and chemical amendments***
Improvement of soil health is associated with consistent diversity of functional microbiota that will result in environmentally resilient and higher-yielding crops (De Corato, 2020). Soil organic formulations (compost, organic residues, organic wastes, biochar, peat etc.) can be used for supporting the growth and proliferation of functional microbial groups. Bio-fumigation, as an organic soil conditioning, is a strategy to suppress diseases via soil fungistasis. Amendment with organic conditioners can enrich the soil with positive, functionally more efficient, and interrelated species of microbes compared to supplementation with chemical fertilizers. Functional characterization of positive microbial groups in response to specific and optimum organic amendment applications for particular crop/soil type will help to better understand the biochemistry of soil health and establish sustainable soil health.
Plant-oriented signalling molecules *viz*., salicylic acid and various metabolites in root exudates, strongly affect the dynamics and composition of microbiome, inferring that plant microbiomes can be artificially modulated using such microbe-stimulating chemicals in an efficient and precise manner. Phenolic compounds like coumarins exudates are helpful in altering the composition of root-colonizing microbes and the protective role of coumarin have been reported for plants against soil-borne pathogens by facilitating the growth of beneficial rhizobacteria. In maize plants, root exudates *viz*., benzoxazinoids protect plants from herbivore insect attacks by favouring the selection and colonization of beneficial bacterial and fungal microbial groups in the rhizosphere. Further investigations on different root exudates combinations i.e. malic acid, coumarins, benzoxazinoids, and camalexin etc. towards microbiome engineering and chemical communications between a particular signalling molecule and microbial group will help to develop host-specific biofertilizers.

Strategy 2: Microbiome engineering using artificial microbial consortia
The function and structure of plant microbiomes can be modulated in a more specific manner by microbiome engineering encompassing the use of artificial microbial consortia (AMC). This approach enables to establish AMC equipped with multiple functions relevant to plant growth and development under normal and challenging environments. Such a strategy provides the best alternative to cope with various drawbacks associated with traditional biofertilizers, such as their inability to compete with microbes under field trials, compromised performance under local environment, and host compatibility issues. The fabrication of an ideal AMC is a systematic approach involving a series of steps i.e. selection of microbe origin, excavating and culturing the core microbiota, identification of functionally active microbial groups, fine-tuning the microbe–microbe interactions, and the evaluation of consortium efficacy. Numerous microbes establish complex interaction networks with other microbes in the rhizosphere, and become a key part of the functional consortia, e.g. plant growth promoting rhizobacteria (PGPR) and AM fungi can complement one another with respect to ecosystem functioning and nutrient availability. Co-inoculation of AM fungus

Claroideoglomus claroideum and plant-beneficial bacterium *Pseudomonas libanensis* into sunflower rhizospheres promoted plant growth by stimulating the growth of plant-beneficial microbiota under salinity or metal stress and treating chili plant roots with a bacterial consortium including *Acinetobacter* sp., *Bacillus velezensis*, and *Bacillus amyloliquefaciens* promoted the plant growth and disease suppressive ability against soil-borne *Phytophthora capsica*. In addition, *Agrobacterium* sp. modulated the bacterial community shift in rhizospheric region by promoting the growth of various PGPRs, e.g., *Brevibacterium* spp. and *Actinomycetes* spp. The *Agrobacterium*-induced microbial community shift exerted beneficial effects to bean plants by increasing overall plant biomass, antioxidants, flavonoids, potassium content, and root nodules. Moreover, co-inoculating the rhizospheres of tomato with *Stenotrophomonas maltophilia* and *Pseudomonas stutzeri* boosted the plant growth and stimulated the production of diffusible compounds i.e., dimethyl disulphide, which are active against the foliar pathogen *Botrytis cinerea*. Two synthetic microbial communities, comprising bacterial strains with 1-aminocyclopropane-1-carboxylic acid deaminase activity, were recently constructed, and these synthetic microbial consortia showed antimicrobial potential against *F. oxysporum* f. sp. *lycopersici* and promoted the growth of tomato plants. Similarly, co-inoculation of pea plants with *Pseudomonas aeruginosa*, *Trichoderma harzianum*, and *B. subtilis* enhanced the defense response against *Sclerotinia sclerotiorum* through regulating antioxidant enzymes activities and accumulation of phenolic compounds upon pathogen attacks. Application of co-cultures of *Azospirillum* sp. and *P. fluorescens* was also effective in controlling the root rot disease of cotton caused by *Rhizoctonia bataticola*. However, sustainability of synthetic microbial consortia needs to be considered under field conditions, and may be achieved through continuous applications of AMC at regular intervals to stabilize microbial consortia over the generations of host plants.

Strategy 3: Host genotype-dependent microbiome engineering

Plant genetic machinery plays a key role in shaping and functioning of microcosms, e.g., *Pseudomonas simiae* WCS417r boosted the biomass production in *Arabidopsis* plants of some accessions. The phyllospheric microbial diversity was altered in mutant *Arabidopsis* plants defective in PTI signaling pathway and MIN7 vesicle-trafficking pathway. This suggested a strong genetic connection between *Arabidopsis* plants loci (controlling plant defense and cell wall integrity) and phyllospheric bacterial diversity. Mutant rice plants, deficient in jasmonate synthesis, showed a significant reduction in *Azoarcus olearius* colonization. At the microbiome level, distinct plant genotypes also attract a variable range of disease suppressive and beneficial microbes, and reassemble their microbial diversity via variations in metabolites exuded from the roots. Some bacterial groups belonging to the genera of *Enterobacter* and *Kosakonia* are more abundant in the rhizobiomes of banana cultivars, and protect against *Fusarium* wilt. Similarly, bean genotypes significantly affected the microbiome assembly in the rhizosphere, with only *0.7%* operational taxonomic units *(OTUs)* in common. Strong genetic correlations were detected among the diversity of epiphytic microbial population, maize plants, and their resistance to southern sheath blight pathogen *Cochliobolus heterostrophus*, and the γ-aminobutyric acid pathway was responsible for controlling the phyllospheric microbial diversity and southern sheath blight susceptibility in maize. Hence, selection and breeding of 'microbe-friendly' cultivars have tremendous potential for improved agricultural productivity. Knowledge on beneficial associations between plants and microbes has provided opportunities to manipulate the plant genome to attract and stabilize the functional microbes existing in the microcosm. To achieve this goal, 'designer plants' can be genetically modified to release exudates and hormones that support the recruitment and colonization of beneficial microbiomes. Wild species or relatives and land races may play important role in exploring genes linked with the assembly of beneficial microbiomes. For example, wild bean accessions had abundant bacteroidetes, while modern domesticated accessions showed *Proteobacteria* and *Actinobacteria* in relatively high abundance. How host genotype–microbiome cross talk recruit's beneficial microbial groups for achieving desirable traits, and how plants modulate and favour the colonization of specific microbiomes need to be investigated to devise ways to maintain functionally active and beneficial microbiomes, as well as to track the real time changes in microbial diversity under field conditions.

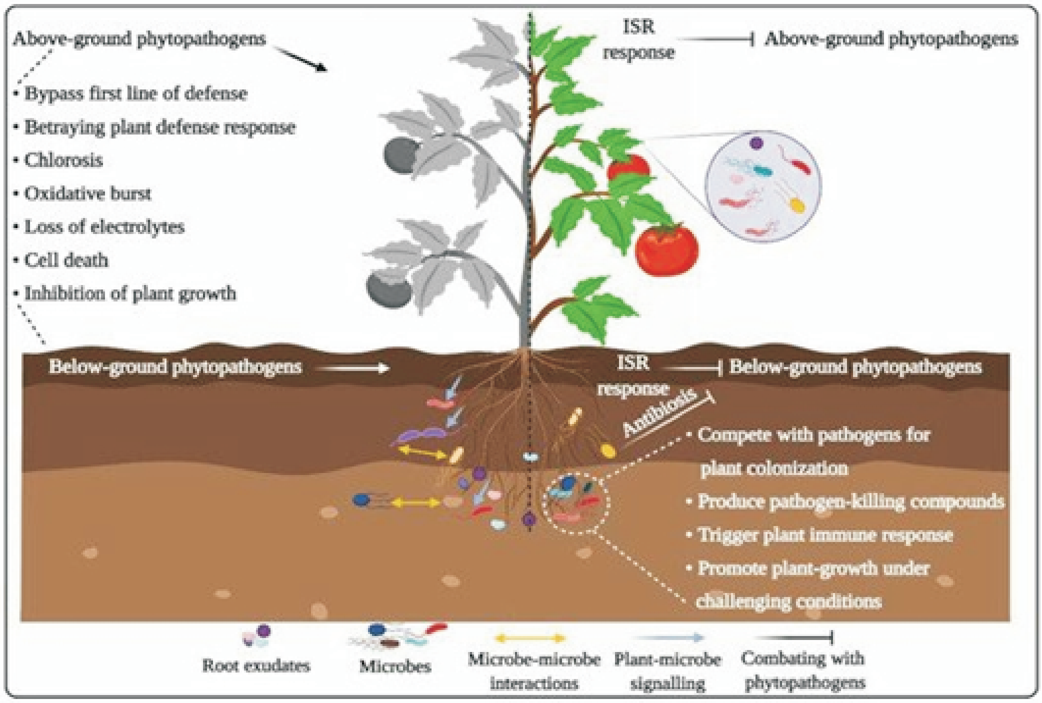

Figure 8.3 Beneficial impacts of positive plant–microbiota interactions on plants

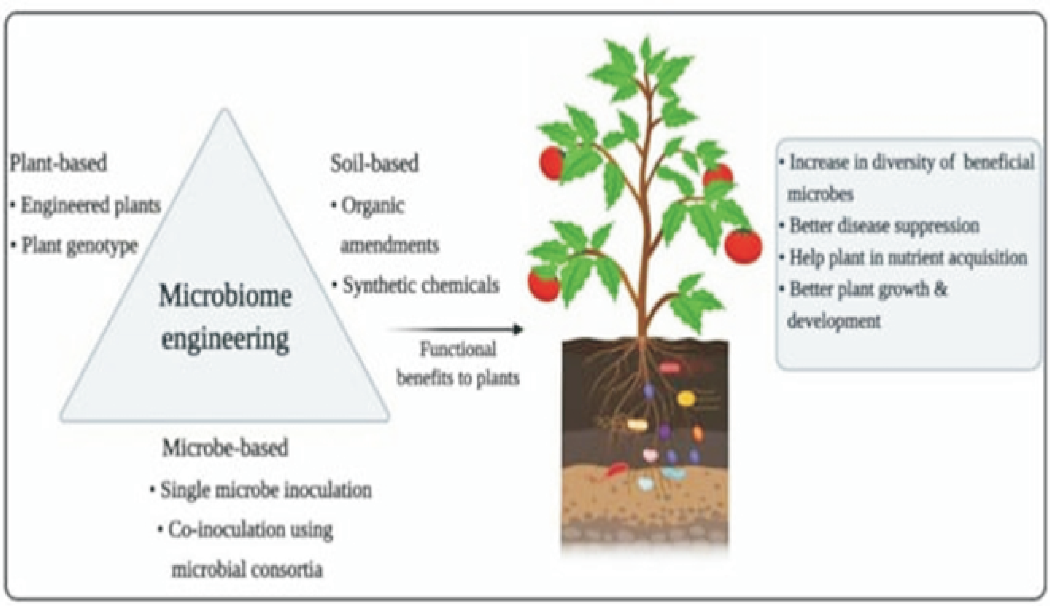

Figure 8.4 Different microbiome engineering approaches for improving the plant health under adverse environmental conditions.

Conclusions and future outlook

Integrated approaches of experimental biology, multi-omics, and computational biology have provided quantitative insights into plant–microbiome interactions and the underlying mechanisms. However, more studies regarding microbial diversity are required to discover the functional consortia of microbes for agronomically important crop plants. Systematic approaches will be required to identify core microbiota and their functions in host plants and to characterize microbiomes of economic and ecological importance in relation to sustainable disease management. Intensive genomic studies have predicted key players that contain functional genes for colonizing plants, plant fitness traits, and their influence on the assembly of plant-microbiota. Although these techniques have unraveled the effects of microbiomes on plant fitness under challenging environments, large proportions of variations are not fully understood. Large-scale longitudinal studies are required to develop baseline for plant–microbiome interactions with clear consideration of host age and temporal dynamics to elucidate leftover knowledge gaps. Improved understanding about the dynamic interactions of plant–microbiome with challenging environmental conditions will give a way forward to engineer microbial consortia with robust outcomes and predicted behavior. Furthermore, coupling experimental approaches with modelling will accelerate the scientific advancement by resolving methodological and technical challenges associated with the plant–microbiome world. Integrative approaches, combining the knowledge from different scientific disciplines, will help to engineer and boost the activities of complex microbial consortia in a consistent and precise manner. Improved knowledge about the dynamics of plant–microbiome–environment interplay will pave the way for the deployment of engineered microbial consortia for sustainable and improved plant production under a continuously fluctuating environment leading to achieve the notion of microbiome-mediated smart agriculture system (MiMSAS) for increasing crop productivity and environmental sustainability (Fig. 8.5).

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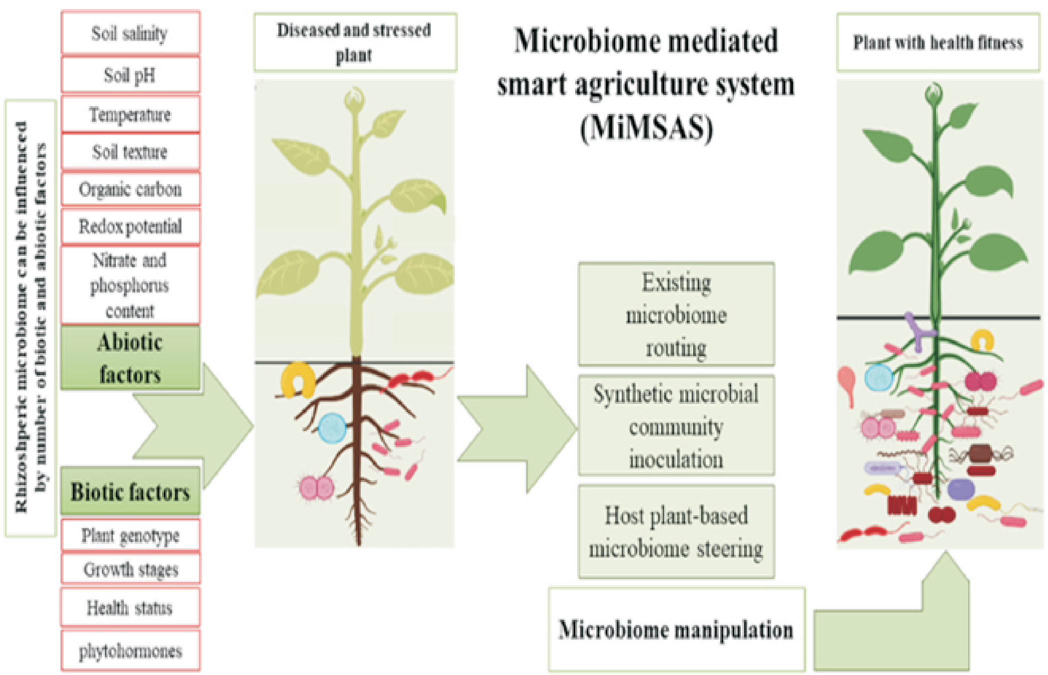

Figure 8.5 Microbiome-mediated smart agriculture system for increasing crop productivity and environmental sustainability (Source: Bano et al. 2021).

9. **ENTREPRENEURSHIP: BIOPESTICIDE RESEARCH AND PRODUCT DEVELOPMENT**

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Abstract: Globally, the biopesticides market is expected to elevate at a Compound Annual Growth Rate (CAGR) of 14.7 per cent from USD 4.3 billion in 2020 to 8.5 billion by 2025 due to increase in awareness of pesticide residue-free food, sustainable environment and the importance for organic products. Biopesticide products are mainly applied in horticultural and agricultural crops, but in most recent times, there is also an increase in demand for biopesticides from recreational parks, theme parks, and golf courses to control pests and suppression of plant diseases. The biopesticides market is segmented by products (bio-herbicide, bio-insecticide, bio-fungicide etc.), formulation (liquid formulation and dry formulation), ingredients (microbial pesticide, plant pesticide, and biochemical pesticide), mode of application (foliar spray, seed treatment, soil treatment and post-harvest) and application (crop-based and non-crop based). In order to cater the demand of availability of biopesticide to the end user, skill development and entrepreneurship among the unemployed youth is the need of the hour. The commercialization of the biopesticide opens the avenue of cottage industry as there is a huge scope to enhance production and use of biological control agents as there is ever increasing demand of these eco-friendly agents.

Introduction

Global population has been projected to reach 9 billion by 2050 and to fulfil the demand of food for this increasing population, the food production needs to be increased by 70 per cent. Urbanization, infrastructure development, fluctuating fuel prices, shrinkage of natural resources, food crisis and climate change are the various challenges which further aggravate the situations. Out-break of biotic and abiotic stresses driven by climate change reduced the agriculture production by 20 per cent. A 10-30 per cent yield losses from pests and additional post harvest losses have been estimated (Thind, 2015). Losses up to 6, 10, 18 and 13 per cent have been estimated in cereals and pulses, oilseeds, fruits, and vegetables respectively, during harvesting, handling and storage (Jha et al., 2015). To avert the losses caused by plant pathogens, fungicides worth 16 billion US dollars are being used per annum. Chemical pesticides being the highly effective have been successfully used for the control of pests, but their indiscriminate and non-judicious uses has resulted in several problems such as development of resistance in pests against pesticides, resurgence of minor pests, pollution of water, air and soil, elimination of natural enemies, disruption of ecosystem and residual effects in the produce etc. Further, phytosanitary standards, environmental and socially unacceptable cultivation practices have emerged as barriers to international trade. Besides, the consumers of the importing countries are rejecting questionable and objectionable products (residue in produce) resulting in heavy losses to the exporters. In the meantime, many traditional chemical pesticides have been withdrawn from the use as a result of environmental and health concerns (Damalas and Eleftherohorinos, 2011).

Central Insecticides Board and Registration Committee has banned 50 Pesticide formulations for import, manufacture and use (https://ppqs.gov.in/sites/ default/files/list_of_ pesticides_which_are_ banned_ refused_registration_and_ restricted_ in_use_as_on_01.10.2022. pdf). All these created an urgent need to adopt suitable non-toxic and eco-friendly alternative method as available to chemical pesticides.

Use of bio-pesticides, the naturally occurring formulations made from the substances that control pests by non-toxic mechanisms and in eco-friendly manner, is not a new technology. These have been used in various forms since human civilization. Biopesticides, being a living organism (natural enemies) or their products, pose less or no threat to the environment and to human health, hence may be freely used for the management of pests.

Fungal Biological Control Agents: The different fungi have been used for the management of plant diseases of agricultural and horticultural crops. Morphologic characteristics of some of the fungal biological control agents as described by Cook and Baker (1983) are as given below:

- ***Pythium oligandrum:*** Sporangia are terminal or intercalary sub-spherical, 25–50 micrometer diameter. Zoospores (20–0) are formed in thin-walled vesicles and are released on maturity. Zoospores are longitudinally grooved, reniform and bi-flagellate. The sexual spores (oospores) are hyaline or yellow, sub-spherical with thick wall bearing spiny pointed protuberances. The oospores are highly resistant to adverse environmental conditions.
- **A*mpelomyces quisqualis:*** Asexual spores (conidia) are formed in superficial pycnidia with thin walls. Conidia are non-septate, pale brown, thin-walled and smooth which may be straight or curved or cylindrical or fusiform.
- **C*ladosporium cladosporioides:*** Asexual spore-bearing structures, conidiophores are erect and pigmented which produce irregular branches at the apical ends. Conidia are hyaline (colourless) or pigmented, smooth or rough ellipsoidal and non-septate and are formed in chains.
- ***Coniothyrium minitans:*** Globose pycnidia are superficial and smooth and are covered by a black carbonaceous envelope. Pycnidiospores are released through the ostiole (opening) as black slimy mass. Individual spores are brown, elliptical and smooth.
- ***Gliocladium virens:*** Conidiphores form side branches at the apical ends and produce ? ask-shaped phialides bearing conidia. The conidia are smooth and elliptical in shape. Thin-walled, globose chlamydospores are also formed facilitating its overwintering.
- ***Myrothecium verrucaria:*** Branched conidiophores are formed in large numbers in the sporodochium with black mass of conidia, surrounded by white ? occose margin. Individually conidia are fusiform with one pointed and the other protruding end fan-tailed and truncate.
- ***Penicillium oxalicum:*** Long brush-like conidia bearing branched conidiophores that end in sterigmata on which smooth and elliptical conidia are borne.
- ***Phialophora graminicola:*** Hyaline to brown branched conidiophores which end in ? ask-shaped phialides which produce hyaline or slightly yellowish single-celled conidia.
- ***Sphaerellopsis filum:*** Specialized spore-bearing structures (pycnidia) have ostiole (opening) through which conidia are released. Septate hyaline to pale brown conidiophores having phialides at the terminal end are formed from the inner walls of pycnidia. Hyaline to pale brown elliptical conidia with a septum are borne on phialides.
- ***Trichoderma viride:*** Conidiophores are erect, septate and branched which produce phialides at the terminal ends. Phialides are single-celled, green, bearing globose or ovoid conidia in large numbers which gather to form ball-like groups. Chlamydospores may be intercalary or rarely terminal and help in the perpetuation of the fungus during adverse conditions.
- ***Trichothecium roseum:*** Conidiophores are hyaline and septate, formed singly or in groups.These are erect, straight or ? exuous, simple or branched. Hyaline, smooth, oblong two-celled conidia are produced on the conidiophores in fragile chain-like cluster.
- ***Verticillium lecanii:*** Erect, septate conidiophores bear solitary or in whorls of 3– phialides. Cylindrical or ellipsoidal conidia are grouped as parallel bundles or heads.
- ***Beauveria* spp*:*** In culture, *B. bassiana* rows as a white mould It produces numerous dry, powdery conidia in distinctive white pore balls on most of the common cultural media. Each spore ball is composed of a cluster of short and ovoid conidiogenous cells, which terminate in a narrow apical extension called a rachis The rachis elongates after each conidium, resulting in a long zig-zag extension. The conidia are single-celled, haploid and hydrophobic
- ***Metarhizium anisopliae:*** Colonies of the fungus grow slowly, and are floccose initially, later becoming olivaceous green due to abundant conidial production. Conidiophores aggregated dense tufts, with repeated, more or less verticillate branching phialides are dense with parallel arrangement, clavate, 9-14 micrometer long with rounded apex. Conidia are produced in long chains, cylindrical, 5-8 x 2.5-3.5 um , thick-walled and yellowish-green in mass.

- ***Lecanicillium lecanii:*** Ten days old colonies on malt agar, oatmeal agar or potato dextrose agar appear thin cottony white or creamy the reverse of which is colourless to pale or deep yellow. Hyphae are 1-2 micrometer wide and phialides are formed singly, in pairs or in whorls of 3 or 4 on poorly developed conidiophores, and are much like the vegetative mycelium. Conidia are ellipsoidal to cylindrical with rounded ends and are produced singly and in aggregate in heads at the tips of the phialides. Chlamydospores are absent whereas, blastospores are formed submerged in culture.
- ***Nomuraea rileyi:*** Colonies grow slowly on malt-agar medium, attaining a diameter of 0.7-1.2 cm within one month at 25°C. These consist of a basal felt from which erect conidiophores arise which are close together. Occasionally, they are covered with a floccose overgrowth of aerial mycelium and the conidial structures appear in a localized area. Conidiophores are erect, setate and arise from the submerged hyphae. These are up to 160 micrometer in length and 2-2.5 micrometer in diameter, forming dense clusters of branches, each bearing two or three compacted phialides, around the stalk. Conidiogenous structures are smooth-walled and hyaline to slightly green. The branches measure 4-6.5 x 2.2-3.5 micrometer. Phialides measure 4.7-6.5 x 2.3-3 micrometer, usually short cylindrical, occasionally with a swollen base. Conidia are produced in dry divergent chains. These are broadly ellipsoidal, sometimes cylindrical or nearly so, smooth-walled measuring 3.5-4.5 x 2-3.1 micrometer pale green and green in mass. In nature, the fungus covers insect larvae, with a thin white felt of hyphae from which compacted conidiophores arise, forming a somewhat pale green layer. Because of its slow growth, *N. rileyi* is rather difficult to cultivate and its growth is very poor to scanty.
- **H*irsutella thompsonii:*** Colonies on potato dextrose agar appear grey, raised, cottony, with grey coloured reverse. Hyphae are 1.5-2 micrometer wide and smooth. Conidiogenous cells arise singly at intervals from the vegetative hyphae and are mono - or polyphialidic, unevenly verrucose, with a broad-based inflated portion, 2-2.5micrometer wide at the base, conical to flask-shaped, increasing more or less to 2-3.5 micrometer wide at the broadest part and then decreasing abruptly to 2-5 micrometer long neck, which is often branched once and rarely two or more times, bearing enteroblastic conidia singly at the tip of each branch. Conidia are spherical, strongly verrucose and 2.5-3.5 micrometer diam.
- ***Chaetomium globosum:*** Colonies grow rapidly, with a pale or olivaceous aerial mycelium and often with yellow, greyish-green, green or red exudates. Ascomata is spherical, ovoidal or obovoidal. Peridium is brown and composed of textura intricate. The fungus has numerous ascomal airs which are usually un branched, flexuose, undulate or coiled, septate and brownish and up to 500 long. Asci are clavate, measuring 30-40 x 11-16 micrometer and 8-spored. Ascospores are limoniform, bilaterally flattened, usually brownish, 9-12 x 8-10 x 6-8 micrometer , with an apical germ pore.
- **C*lonostachys rosea:*** Colonies become 40-50 mm in diam. in 7 days at 24°C Reverse of the colony on oatmeal agar appear greyish green to olivaceous-green or pale to light yellow or pale orangewhen incubated in dark and day-light. However under UV, older colonies generally appear with greenish hues because of the colour of conidial masses, frequently with yellow pigments at the margin and outside the colony. Conidia are hyaline, minutely curved, distally broadly rounded or slightly tapering, with a laterally displaced hilum. Perithecia and stroma not observed.

Bacterial Biological Control Agents

- ***Agrobacterium radiobacter* 84:** It is effective against crown gall disease. The bacterial cells are small, short rods and non-spore-forming. They are motile by polar flagella. The bacteria is not acid-fast, gelatin lique? ed, starch hydrolyzed and no milk coagulating.
- ***Bacillus subtilis:*** Effective in suppressing the diseases caused by soil-borne fungal pathogens. It has slimy cells and produces oval endospores, strictly aerobic and produces extracellular amylases and proteases.

- ***Erwinia herbicola:*** It is effective for the control of ?re blight disease caused by E. *amylovora*. It has gram-negative, rod shaped slime cells with peritrichous ?agella. It is facultative anaerobe and does not produce indole, but produces phenylalanine deaminase and hydrogen sul?de.
- ***Pseudomonas fiuorescens:*** It is effective in suppressing several soil-borne, seed-borne and air-borne diseases. The bacterial cells are rod- shaped, gram-negative with multitrichous ?agella. It liquefies the gelatin, oxidase positive, arginine dihydrolase positive and produces soluble ?uorescent pigments.
- ***Streptomyces griseus:*** It has ?lamentous cells and usually produces mycelium-like structures and form spores by fragmentation of hyphal cells. Sporophores are straight, ?exuous or fascicled; produces antibiotics effective against microorganisms.

Benefits of Fungal and Bacteria Antagonists

- It offers efficient control of plant diseases with a wide range of actions.
- These have high level of propagation in the soil with increase in populations and exerting long-term control over phytopathogenic fungi.
- It helps to decompose organic matter and convert nutrients into the forms utilizable by the plant so have an indirect effect on crop nutrition.
- It stimulates crop growth because it has metabolites which promote the development processes in plants.
- It can be applied to decompose compost or organic matter to accelerate the process of maturation.
- It favours the proliferation of beneficial soil organisms, such as other antagonistic fungi.
- It does not need a safety period before harvesting. It is environmental friendly and reduces or eliminates the use of fungicides and bactericides.
- It economizes the cost and dependence of crop production and prevents disease by protecting the roots and leaves and promotes root and root hair growth.
- It improves nutrition and water absorption with no phyto-toxic effect.
- It acts as a bio- degradant of agrochemicals
- It metaboliozes the nutrients for plants.
- It can be used as weedicide.
- It protects farm and botanical seeds from phyto-pathogens.
- It is compatible with Mycorrhizae, Azotobacter and other biofertilizers.
- It is also compatible with bioagents that control pests and diseases.

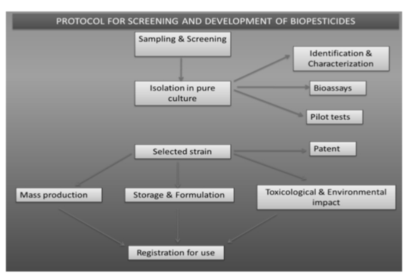

Figure 9.3 Protocol for screening and development of pesticides

Application of fungal antagonists

Seed treatment: The talc-based formulation is used as a dry seed treatment @ 4 g/kg and the treated seed can be sown immediately.

Seedling root dipping: Dissolve 10 g of formulation in 10 lt. water. The seedlings, after pulling out from the nursery can be dipped in the BCA suspension. A minimum period of 10 minutes is necessary for soaking the roots and prolonged dipping will enhance the efficacy.

Nursery treatment: Mix 500 g of the formulation in the 100 lt. of water and drench nursery beds (10 cm depth), immediately after sowing seeds. Use1.25 kg of FYM impregnated with BCA formulation in the nursery beds at the time of mulching of nursery beds.

Soil application: Mix 1 kg of formulation with 50 kg of FYM spread in 3 X 6 m beds and moisten it. Keep it covered for 3-4 days. Turn FYM and moisten again 3-4 times. After 15 days apply/spread the prepared FYM mixture over one acre land

Foliar application: Spray the product @ 2.5 kg / ha in 800 lt. of water at 10 days interval for 2 times depending on disease / pest infestation / intensity. If there is no disease incidence, a single spray is sufficient.

Mass production of biocontrol agents

Biocontrol agents (BCAs) form the first and second line of defence in integrated pest management and their application on large scale requires their large scale production. In order to achieve that, use of different growth media and upscaling in bioreactors have been carried out together with standardization of growth conditions for harvesting maximum biomass of BCAs. The growth of biopesticide market has encouraged agribusinesses and universities to explore ideal, easily available, low cost, offering substrates which may support maximum colonization alongwith scale-up of technologies to achieve the highest microbial growth on a large scale. The growth media used should be an optimal source of carbon, nitrogen, mineral salts and growth factors as the medium composition affects the type, shape, fitness and quantity of produced propagules (de Rezende et al., 2020). For mass production of *Trichoderma viride,* generally molasses yeast medium, rice and wheat grains are used (Kumar et al.,2014;Mendoza-Mendoza et al., 2016). A new approach utilizes agricultural wastes like cassava peels, banana pseudostem, coconut shell, pineapple peels (Zhang et al., 2022) and sugarcane bagasse (Sachdev et al., 2018) as substrates for mass multiplication of *Trichoderma* spp. which is an eco-friendly step towards resource recycling. A higher C:N ratio in the substrate composition generally increases the sporulation of *Trichoderma* spp. and benefits its biocontrol activity (de Rezende et al., 2020).

Commonly used BCAs such as *Trichoderma asperellum* and *Bacillus subtilis* are mass multiplied through liquid, solid state and submerged liquid fermentation methods. Liquid state fermentation (LSF), uses soluble materials in water for the microbial growth (Mendoza-Mendoza et al., 2016). The quantity of water used should be in the specified limits and the substrates should be inexpensive and exhibit good nutrient profile since only the raw material accounts for 35–40 per cent of the production cost (Kumar et al.,2014). Some of the substrate medium commonly and widely used for mass production of *Trichoderma asperellum* include Potato Dextrose Broth, V-8 Juice, Molasses-yeast medium and Wheat bran (Vehapi et al., 2023) whereas, for *Bacillus subtilis Nutrient broth is commonly used*. In solid state fermentation (SSF), insoluble materials or solid substrates like cereal grains (sorghum, millets, ragi) are used for the microbial growth. The microbe can be cultivated on natural substrates or on an inert support impregnated with a liquid medium and the latter is suitable only for small scale and individual level production (Kumar et al., 2014). Solid-state fermentation (SSF) is energy efficient and provides micro propagules with higher aerial conidia content and viability. However, it's scale-up is laborious and time consuming (de Rezende et al., 2020). Furthermore, uniformity of product quality among different batches is a significant and main drawback. Submerged liquid fermentation (SLF) overcomes these limitations as it is cost-effective and automated on large scale. *Trichoderma* conidia are grown in liquid media for aerobic fermentation in bioreactors leading to production of diverse and viable propagules. In SLF, parameters such as pH, temperature, aeration, water activity and dissolved oxygen concentration are easily monitored which is helpful in the quality production of BCA (de Rezende et al., 2020).

Stability and composition of formulation influences the efficacy of biocontrol- product. An ideal formulation should be effective, stable under diverse environmental conditions, safe to use, eco-friendly, broad spectrum, easily available, cost effective with increased shelf life (Kumar et al.,2014). *Trichoderma asperellum* formulations contain propagules like conidia, mycelium and chlamydospores, and conidia are the active ingredient whereas, chlamydospores are the most stable (de Rezende et al., 2020). The formulations can be talc, oil, coffee-husk, banana waste, vermiculite, wheat bran, alienate pills, pasta granule and press mud based (Kumar et al.,2014). Hence, it is required to develop a suitable formulation for all types of propagules aiming to improve biocontrol efficacy, persistent in the field and with extended shelf-life under normal conditions. *Bacillus subtilis* formulations targeting fungal diseases are usually available in aqueous suspension and dry flakes (talc based) (Kumar et al.,2014). In addition to the private sector undertaking this research in public sector, will greatly expedite progress in this important and critical area to advance the successful incorporation of biocontrol products into the mainstream of tools to manage plant diseases in production agriculture.

Registration of Biocontrol Agents

There are two major categories of biological pest control agents i.e. biochemical pest control agents (semio-chemicals, hormones, enzymes and natural plant regulators and insect growth regulators) and the microbial pest control agents (virus, bacteria, fungi, protozoa or genetically modified micro-organisms). In a biochemical pest control agent, a chemical must exhibit a mode of action other than direct toxicity in the target pest i.e. growth regulation, mating disruption, attraction etc. It must be naturally occurring, or if the chemical is synthesized by man, then it must be structurally identical to the naturally occurring chemical. There is difference between nature of biological and biochemical pest control agents and some data requirements for registration would differ in both the cases. However, the general principle should be that the product should demonstrate effectiveness, it should be non-hazardous to users, consumers and/or the environment.

The Food and Agriculture Organization of United Nations provides certain guidelines for the data requirements to register BCA which include: Identity of the product-nature of active agent and the finished product, Intended uses and method of application, experimental data, toxicology data, residue data and environmental fate studies (Active Agent). Under Section 9(3) of Pesticide Act of India 1968 [Kumar et al.,2014], for registration of biopesticides the following information needs to be provided:

i) Systemic name and common name of the bio control agent
ii) natural occurrence
iii) morphological description of the of the bio agent
iv) details of manufacturing process
v) mammalian toxicity
vi) environmental toxicity
vii) residual analysis.

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10. INDIAN SCENARIO OF INSECT AND MITE PESTS OF HIGH VALUE CROPS UNDER PROTECTED AGRICULTURE

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Abstract: Protected cultivation of high value crops has emerged as the single most significant technology for ensuring high production, higher quality and lucrative returns in the context of market globalisation, diminishing land resources and climate change. Recently, area under protected agricultural land has grown significantly throughout world. Protected agriculture creates a consistent and hospitable microclimate that is ideal for reproduction and spread of insect-pests, and it has emerged as a potential constraint for successful crop production in a protected environment. Arthropod pests like mites, whiteflies, thrips, leaf-miners, and aphids are the main cause of crop losses. In India, 60 insect and mite species from 10 different groups have been identified to be associated with vegetable, flower and fruit crops grown in protected environments. It compising 12,10,9,8,7,5,2 each and 1 species of mites, thrips, caterpillars, aphids, beetles, mealy bugs, leaf miners, of bugs and whiteflies, and leaf hoppers, respectivly. Amongst these 44 species are sap feeders. Aphid, whitefly and mites are of significance under protected environment which inflict severe losses to the crops across India. *Bemisia tabaci*, *Myzus persicae* and *Tetranychus urticae* are more abundant in the north, while *Polyphagotarsonemus latus* is widespread in the southern India. *Trialeurodes vaporiorum* is primarily restricted to Himachal Pradesh, while *Tuta absoluta* is widespread throughout India.

Introduction

Protected agriculture is the cropping technique where the microclimate surrounding the plant is controlled partially/ fully as per the requirement of the plant species cultivated during their growth period. It has become popular worldwide with the progress of liberalized economy and the advent of newer technologies in agriculture. Protected cultivation offers distinct advantages of quality, productivity, favourable market price and additional remuneration for high quality produce. Faced with constraints of land holdings, rapid urbanization, declining crop production, and biodiversity, and ever-increasing population, demand for food, especially vegetables have increased manifold. Under these circumstances protected cultivation has offered a new dimension to produce more in a limited area. With the advancement in agriculture, several protected cultivation practices have been adopted massively in commercial farming. Among these protected cultivation practices, greenhouse, plastic-house, artefact-house, net-house and shade house are in practice in India, amongst them commonly used structures are greenhouses. A greenhouse is a framed or inflated structure lined with a clear or semi-transparent material in which crops may be fully-grown underneath the conditions of a minimum of partly controlled setting (Pattnaik and Mohanty, 2021). In India, protected cultivation of vegetable crops is in infancy; however, concerted efforts by different developmental agencies in the last two decades have resulted in enhanced area under all forms of protected cultivation. Presently, the total space covered under protected cultivation in the country is approximately 30,000 ha and states of Maharashtra, Karnataka, Himachal Pradesh, North-Eastern states, Uttarakhand, Tamil Nadu and Punjab are the leading ones (Pattnaik and Mohanty, 2021). Among different crops grown under protected environment in India capsicum, carnation, chrysanthemum, cucumber, gerbera, lilium, rose, strawberry, tomato etc. are the most extensively grown vegetables and flower crops. However, it provides stable and congenial micro-climate which is favourable for multiplication of insect- pests which hamper crop growth and become one of the major limiting factors for successful crop production (van Lenteren, 2000; Sood, 2010, Kaur et al., 2010; Ghongade and Sood, 2018).

Under field conditions often, the natural regulating factors such as predators and parasitoids keep pests under control, however, these are not present in protected environment. Hence, pests develop more rapidly in the indoor environment than the outdoors. Crop losses in greenhouse crops are mainly due to arthropod pests like mites, whiteflies, thrips, leaf-miners, aphids (Singh *et al.,* 2017; Sood *et al.,* 2018; Ghongade and Sangha 2020; Ghongade and Sood 2021; Sharma *et al.*, 2021). The damage inflicted by arthropod pests in greenhouse crops varies with the pest and season.

Studies undertaken in mid-hill regions of Himachal Pradesh under protected environment revealed that greenhouse whitefly (*Trialeurodes vaporariorum)*, two spotted spider mite (*Tetranychus urticae)* and aphid (*Myzus persicae)* completed 14, 28 and 38 generations in a year, respectively (Anjana Devi, 2011; Sood et al., 2014; Sharma, 2015) and are responsible to cause direct and indirect loses. The infested leaves become yellow, curl, dry up and finally drop down (Saha et al., 2020). Regulated and balanced crop with various plant nutrients can influence host plant susceptibility to sucking insect-pests. Crops grown under protected environment are known for improved quality. All plant nutrients may affect plant health but nitrogen and potassium, and the essential macronutrients, play a major role. Most studies revealed that generally excessive use of nitrogenous nutrion decreases crop resistance to pests thereby, increasing food consumption, survival, growth, reproduction and population, whereas potassium increases the crop resistance. It was reported that high N (125% more the RDF) favoured the population build-up of greenhouse whitefly (GHWF) and resulted in cumulative greenhouse whitefly days to 1187 in summer cropping season, whereas high K level (25% more the RDF) resulted in 846 cumulative GHWF days in the same cropping season (Singh, 2017).

Scanning of vast literature revealed a total of 60 species of arthropod-pests in 47 genera to be associated with vegetable, fruits and ornamentals grown under protected environment in India (Tables 10.1 to 10.3). Out of these, insects were dominating (80%) with 48 known pest species followed by12 species of mite-pests (Fig 10.1). In addition, six unidentityfied species of arthropod pests have also been recorded from different crops and regions.The recorded insect-pests belong to five orders namely, Hemiptera, Thysanoptera, Lepidoptera, Coleoptera and Diptera. Order Hemiptera was found to be dominating with 18 species followed by Lepidoptera and Thysanoptera. Out of the total recorded insect-pests, sap-feeders were having a lion's share of 73 per cent and remaining were biting-chewing types and 18 species were of polyphagous nature.

Insect and non-insect pests associated with vegetable crops

Extensive studies revealed that in India, 51 insect and mite species belonging to ten groups were associated with vegetable crops grown under protected environment. These included aphids, beetles , bugs, caterpillars, leaf miner , leaf hopper, mealy bugs, mites, thrips and whiteflies. Distribution of these pests in different states of India has been depicted in Table 1.1. In capsicum, 8 pest groups were recorded from 12 states, amongst which aphids: *Aphis gossypii*, *Myzus persicae*, caterpillars (*Helicoverpa armigera, Spodoptera litura),* mealy bugs (*Ferrisia virgata, Phenacoccus* spp*),* mite (*Polyphagotarsonemus latus*, *Tetranychus urticae),* thrips (*Scirtothrips dorsalis*, *Thrips tabaci)* and whitefly (*Bemesia tabaci*, *Trialeurodes vaporariorum)* are of great significance. In tomato, eight pest groups were reported from twelve states amongst which, aphids (*Aphis gossypii*, *Myzus persicae)*, caterpillar (*Helicoverpa armigera, Spodoptera litura and Tuta absoluta)*, leaf-miner (*Liriomyza trifolii*) mites,(*Aculops lycopersicae, Polyphagotarsonemus latus*, *Tetranychus ludeni*, *T. Urticae)*, and whitefly (*Bemesia tabaci*, *Trialeurodes vaporariorum).* In cucumber, six pest groups were reported from 14 states. Out of these, aphids (*Aphis gossypii*, *Myzus persicae)*, leaf-miner (*Liriomyza trifolii)*, mite (*Tetranychus ludeni*, *T. urticae)*, thrips; (*Thrips tabaci*, *Thrips palmi)* and whitefly; (*Bemesia tabaci*, *Trialeurodes vaporariorum)* are prominent with more abundance and distribution. Aphids, whiteflies and mites have emerged as serious pests of polyhouse crops causing higher crop damage in different regions of the country eg. *Myzus persicae* and *Tetranychus urticae* are more prevalent in northern region whereas, *Polyphagotarsonemus latus* is common in southern regions. Amongst the pests recorded from the country, *Trialeurodes vaporiorum* is mainly confined to Himachal Pradesh and *Tuta absoluta* is widely distributed India (Table 10.1).

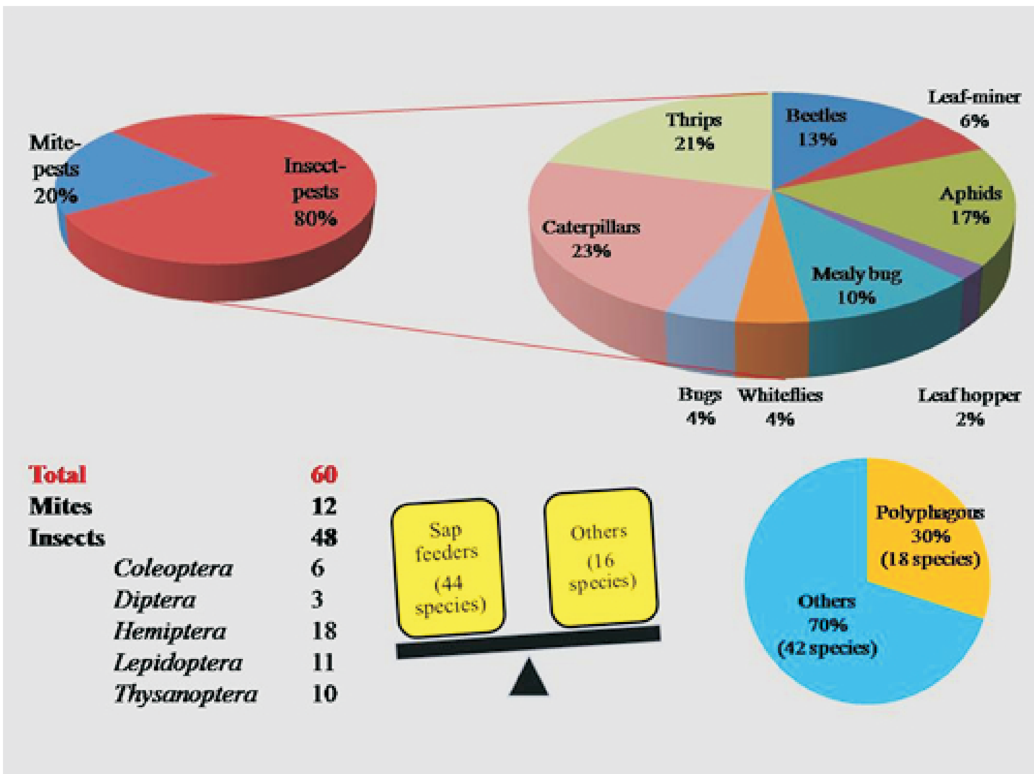

Figure 10.1Scenario of insect and mite-pests of crops grown under protected agriculture in India

Table 10.1 Insect and mite pests of vegetable crops under protected environment in India

Crops	Insect Pest groups	Scientific name	State(s)	References
Amaranths	Mites	*Polyphago tarsonemus latus*	Kerala	Lenin and Bhaskar (2016)
		Tetranychus truncates	Kerala	Lenin and Bhaskar (2016)
Brinjal	Caterpillars	*Tuta absoluta*	Karnataka, Tamil Nadu	Sridhar et al. (2015); Balaji et al. (2018); Sridhar and Kumaran (2018)
		Leucinodes orbonalis	Punjab	Kaur et al.(2004)
	Whitefly	*Bemesia tabaci*	Punjab	Yele et al. (2020)
Bitter gourd	Mites	*Polyphagotarsonemus latus*	Kerala	Lenin and Bhaskar (2016)
Cabbage, Cauliflower and Chinese cabbage	Caterpillars	*Plutella xylostella*	Himachal Pradesh	Vashisth (2009); Sood et al. (2018)
Capsicum/ Sweet pepper	Aphids	*Myzus persicae*	Andhra Pradesh Punjab, Himachal Pradesh; Telangana	Singh et al. (2004); Vashisth (2009); Gavkare et al. (2014); Sharma et al. (2021); Pathipati et al. (2017); Saloni (2018); Verma et al. (2018); Singh and Joshi (2020); Sharma et al., (2021)
		Aphis gossypii	Punjab, Rajasthan, Tamil Nadu, Uttarakhand, New Delhi	Singh et al. (2004); Kaur et al (2010); Singh et al. *(2012),* Kumar (2014), Gupta (2016); Udhaya kumar et al. (2018)
	Beetles	*Longitarsus nigripennis*	New Delhi	Singh et al. (2003); Singh et al. *(*2012)
	Caterpillars	*Agrotis ipsilon*	Andhra Pradesh	Pathipati et al. (2017)
		Helicoverpa armigera	Himachal Pradesh, Punjab	Singh et al. (2004); Vashisth (2009)
		Spilosoma obliqua	Uttarakhand	Kumar (2014)
		Spodoptera exigua	Rajasthan	Gupta (2016)
		Spodoptera litura	Andhra Pradesh, Himachal Pradesh; Karnataka, Maharashtra, Punjab; Telangana	Singh et al. (2004); Vashisth (2009); Nandini et al. (2012); Maruthi et al. (2017); Pathipati (2017); Tompe et al. (2020)
	Leaf miner	*Asphondylia capsici*	Andhra Pradesh, Telangana	Pathipati et al. (2017)
	Mealy bug	*Phenacoccus solenopsis*	Himachal Pradesh, Punjab	Anonymous (2013); Singh et al. (2016); Saloni (2018); Sood et al. (2018)
		Phenacoccus viburni	Punjab	Saloni (2018)
		Ferrisia virgata	Kerala	Thamilarasin (2016)
		Maconellicoccus hirsutus	Uttarakhand	Kumar (2014)
	Mites	*Polyphagotarsonemus latus*	Andhra Pradesh, Himachal Pradesh, New Delhi, Karnataka Kerala, Punjab, Rajasthan, Telangana Uttarakhand al. (2018)	Singh *et al.* (2004); Reddy and Kumar (2006); Nandini et al. (2012); Singh et al. (2012); Kaur et al. (2010); Kumar (2014); Gupta (2016); Lenin and Bhaskar (2016); Pathipati et al. (2017); Saloni (2018); Sood et al. (2018); Sruthi et

		Tetranychus urticae	Himachal Pradesh, Punjab	Ghongade and Sood (2018); Saloni (2018)
		Tetranychus ludeni	Himachal Pradesh	Anjana (2011), Sood et al. (2012), Anonymous (2013); Ghongade and Sood (2018)
		Tetranychus spp.	Himachal Pradesh	Ghongade and Sood (2018)
	Thrips	*Scirtothrips dorsalis*	Andhra Pradesh, Himachal Pradesh, Karnataka, New Delhi Punjab, Rajasthan, Uttarakhand,	Reddy & Kumar (2006); Nandini et al. (2012); Singh et al. *(*2012); Kaur et al., (2010); Kumar (2014); Gupta (2016); Pathipati *et al.* (2017); Sood *et al.* (2018); Sruthi *et al.* (2018); Sunitha and Narasamma (2018);
			Telangana	Mirala and Gopali (2019)
		Thrips atratus	New Delhi	Singh et al. (2012)
		Thrips tabaci	Punjab	Saloni (2018)
	Whitefly	*Bemesia tabaci*	Andhra Pradesh, New Delhi, Himachal Pradesh, Punjab, Rajasthan, Uttarakhand, Telangana	Singh et al. (2004); Singh et al.*,* (2012); Kumar (2014); Gupta (2016); Pathipati et al. (2017); Saloni (2018); Sood et al.*,* (2018); Singh and Joshi (2020); Ghongade and Sangha (2020); Ghongade et al. (2021)
		Trialeurodes vaporariorum	Himachal Pradesh	Vashisth (2009); Kashyap et al. (2016); Singh and Sood (2018); Sood et al. (2018)
Chilly	Mite	*Polyphagotarsonemus latus*	Kerala	Lenin and Bhaskar (2016)
Cucumber	Aphid	*Myzus persicae*	Himachal Pradesh, Kerala	Vashisth (2009); Thamilarasin (2016)
	Caterpillars	*Diaphania indica*	Kerala	Thamilarasin (2016)
		Spodoptera litura	Himachal Pradesh	Vashisth (2009)
	Leaf -miner	*Liriomyza trifolii*	Himachal Pradesh, Kerala Rajasthan	Thamilarasin (2016) ; Banshiwal *et al.* 2018; Sood *et al.* (2018); Sood et al. (2018)
		Liriomyza spp.	Himachal Pradesh	Vashisth (2009)
	Mealy bug	*Ferrisia virgata*	Kerala	Thamilarasin (2016)
			Kerala Rajasthan	*al.* (2018); Sood et al. (2018)
		Liriomyza sp.	Himachal Pradesh	Vashisth (2009)
	Mealy bug	*Ferrisia virgata*	Kerala	Thamilarasin (2016)
	Mites	*Eutetranychus orientalis*	Kerala	Lenin and Bhaskar (2016)
		Polyphagotarsonemus latus	Kerala, Punjab	Lenin and Bhaskar (2016)
		Tetranychus urticae	Andhra Pradesh, Himachal Pradesh, Kerala, New Delhi, Punjab	Deka *et al.* (2011); Reddy *et al.* (2014); Ghongade and Sood (2018); Sood *et al*. (2018); Lenin & Bhaskar (2019); Thakur and Sood (2019); Ghongade and Sangha (2020); Ghongade and Sood (2021); Ghongade *et al.* (2022); Thakur and Sood (2022)

		Tetranychus ludeni	Himachal Pradesh	Anjana (2011), Sood *et al.* (2012), Anonymous (2013)
		Tetranychus truncates	Kerala	Lenin and Bhaskar (2016)
		Tetranychus neocalidonicus	New Delhi	Singh *et al.* (2003)
		Tetranychus okinawanus	Kerala	Lenin and Bhaskar (2016)
		Tetranychus spp.	Kerala	Thamilarasin (2016)
	Thrips	*Astrothrips tumiceps*	Kerala	Thamilarasin (2016)
		Frankliniella schultzei	Kerala	Thamilarasin (2016)
		Thrips hawaiiensis	Kerala	Thamilarasin (2016)
		Thrips tabaci	Rajasthan	Banshiwal *et al.* (2018
		Thrips palmi	Himachal Pradesh	Sood *et al.* (2018)
	Whitefly	*Bemesia tabaci*	Haryana, Punjab Rajasthan	Banshiwal *et al.* (2018); Ghongade (2020); Yele *et al.* (2020); Ghongade *et al.,* (2021); Ghongade and Sangha (2020)
			Himachal Pradesh	Sood *et al.* (2018)
		Trialeurodes vaporariorum	Himachal Pradesh	Vashisth (2009); Kashyap *et al.* (2016); Singh and Sood (2018); Sood *et al.* (2018)
French bean	Leaf-miner	*Liriomyza trifolii*	Himachal Pradesh	Sood *et al.* (2018)
	Mites	*Tetranychus urticae*	Himachal Pradesh	Ghongade and Sood (2018); Sood *et al*. (2018)
		Tetranychus ludeni	Himachal Pradesh	Ghongade and Sood (2018); Sood *et al.* (2018)
		Tetranychus macfarlane	Kerala	Lenin and Bhaskar (2016)
Okra	Aphid	*Aphis gossypii*	Karnataka	Jayasimha *et al.* (2012)
	Leaf-hopper	*Amrasca biguttula biguttula*	Karnataka	Jayasimha *et al.* (2014)
	Caterpillar	*Spodoptera litura*	Himachal Pradesh	Vashisth (2009)
	Mites	*Tetranychus urticae*	Himachal Pradesh, Gujarat, Punjab	Ghongade and Sood (2018); Kaur *et al.* (2019); Patel and Ghetiya (2019)
		Tetranychus cinnabarinus	Maharashtra	Singh *et al.* (2003); Valunj *et al.* (1999); Sabir *et al*. (2013)
Pea	Leaf-miner	*Chromatomyia horticola*	Himachal Pradesh	Vashisth (2009)
Potato	Caterpillars	*Tuta absoluta*	Karnataka, Tamil Nadu	Sridhar *et al.* (2015); Balaji *et al.* (2018); Sridhar and Kumaran (2018)
		Phthorimaea opercullela	Himachal Pradesh	Thakur and Chandla (2013)
Summer squash	Beetles	*Aulacophora foveicollis*	New Delhi	Singh *et al.* (2012)
		Aulacophora foveicollis	New Delhi	Singh *et al*. (2003)
	Mite	*Tetranychus urticae*	Himachal Pradesh	Ghongade and Sood (2018)
Tomato/ Cherry tomato	Aphid	*Aphis gossypii*	New Delhi, West Bengal	Singh *et al. (2012);* Sri *et al.* (2017)
	Beetle	*Epilachna vigintioctopunctata*	New Delhi	Singh *et al*. (2003); Singh *et al. (*2012)
	Caterpillars	*Spodoptera litura*	Himachal Pradesh, West Bengal	Vashisth (2009) ; Sri *et al.* (2017)

	Helicoverpa armigera	Himachal Pradesh, West Bengal	Sri *et al*. (2017) ; Sood *et al.* (2018)
	Tuta absoluta	Himachal Pradesh, Karnataka, Maharashtra, New Delhi, Tamil Nadu, Uttarakhand	Shashank *et al.* (2015); Shashank *et al.* (2016); Sridhar *et al.* (2015); Varshney & Ballal (2017); Balaji *et al.* (2018); Choudhary (2018); Sood *et al.* (2018); Srivastava *et al.* (2018); Manohar *et al.* (2019)
Leaf -miner	*Liriomyza trifolii*	Himachal Pradesh, West Bengal	Sri *et al.* (2017); Sood *et al.* (2018)
	Liriomyza spp.	New Delhi	Shashank *et al.* (2016)
	Liriomyza spp.	Himachal Pradesh	Vashisth (2009)
Mealy bug	*Phenacoccus solenopsis*	Himachal Pradesh	Singh *et al*. (2016); Sood *et al.* (2018)
	Ferrisia virgate	New Delhi	Singh *et al*. (2012)
Mites	*Polyphagotarsonemus latus*	Kerala	Lenin and Bhaskar (2016)
	Tetranychus urticae	Gujarat, Himachal Pradesh, Karnataka	Pokle & Shukla (2015); Ghongade and Sood (2018)
	Tetranychus ludeni	Himachal Pradesh	Anjana (2011); Sood *et al.* (2012); Anjana (2011), Sood *et al.* (2012); Ghongade and Sood (2018)
	Aculops lycopersici	Himachal Pradesh	Kashyap *et al*. (2015); Sood *et al.* (2018)
Thrips	*Thrips tabaci*	West Bengal	Sri *et al.* (2017)
Whitefly	*Bemesia tabaci*	Haryana, Himachal Pradesh, Punjab New Delhi, West Bengal, Karnataka	Singh *et al.* (2012); Sri *et al.* (2017); Sood *et al.* (2018); Yele *et al.* (2020)
	Trialeurodes vaporariorum	Himachal Pradesh	Vashisth (2009); Kashyap *et al.* (2016); Singh and Sood (2018); Sood *et al.* (2018)

Insect and non-insect pests associated with ornamental crops

Distribution of insect and non-insect pests associated with important ornamental crops in different states of India is given in Table 10.2. Species of insect and mite-pests attacking the ornamental crops comprised seven different pest groups of which, thrips (nine species) were pre diminant in Northern and Southern region under protected cultivation. Infestation with four species each of aphids and mites, found on different floriculture crops, with majority on chrysanthemum and carnation throughout India. One species of beetles infesting rose was reported in South regions. Whitefly, a major pest under protected cultivation was found to be associated with rose and gerbera with two important species. Three species of caterpillars were also reported to inflict damage on ornamental crops in north, central and south regions of India.

Table 10.2 Insect and mite pests of ornamental crops under protected cultivation in India

Crops	Pest groups	Scientific name	State(s)	References
Carnation	Aphids	*Myzus persicae*	Himachal Pradesh	Vashisth (2009)
	Caterpillars	*Helicoverpa armigera*	Himachal Pradesh	Vashisth (2009)
	Mites	*Tetranychus cinnabarinus*	Maharashtra	Valunj *et al.* (1999); Singh *et al.* (2003);Sabir *et al*. (2013)
		Tetranychus ludeni	Himachal Pradesh	Anjana (2011); Sood *et al.* (2012); Anonymous (2013)
		Tetranychus urticae	Karnataka, Maharashtra, Gujarat, Himachal Pradesh	Chauhan *et al.* (2011); Patil *et al.* (2014); Tumbada *et al.* (2014); Manju *et al.* (2015); Manju *et al.* (2016; Sandeepa *et al.* (2017); Ghongade and Sood (2018)
	Thrips	*Thrips tabaci*	Himachal Pradesh Karnataka	Vashisth (2009); Manju *et al.* (2015)
Chrysanthemum	Aphids	*Macrosiphoniella sanbornii*	Karnataka	Reddy and Janakiram (2008)
	Mites	*Tetranychus urticae*	Himachal Pradesh	Reddy *et al.* (2014)
Gerbera	Caterpillar	*Spodoptera litura*	Maharashtra	Hole *et al.*(2010)
	Leaf-miner	*Liriomyza trifolii*	Maharashtra, Kerala	Apte (2001); Smitha *et al.* (2017)
	Mites	*Tetranychus cinnabarinus*	Maharashtra	Valunj *et al.* (1999); Singh *et al.* (2003); Sabir *et al*. (2013)
		Tetranychus ludeni	Himachal Pradesh	Anjana (2011); Sood *et al.* (2012); Anonymous (2013)
		Tetranychus urticae	Gujarat, Himachal Pradesh	Shah and Shukla (2014); Ghongade and Sood (2018)
		Thrips palmi	Karnataka	Reddy and Aswath (2008); Sabir *et al*. (2013)
	Whiteflies	*Bemesia tabaci*	Maharashtra, Karnataka	Apte (2001); Reddy and Aswath (2008)
Orchid	Aphids	*Macrosiphum luteum*	Sikkim	Sangma *et al.* (2018)
		Toxoptera aurantii	Sikkim	Nagrare (2004)
Rose	Beetles	*Alcidodes* spp.	Karnataka	Hegde *et al* (2020)
	Caterpillars	*Helicoverpa armigera*	Himachal Pradesh	Vashisth (2009)
		Spodoptera exigua	Karnataka	Rani and Mohan (2000)
	Mites	*Tetranychus urticae*	Karnataka, Himachal Pradesh, Maharashtra	Hegde *et al.* (2020); Patke *et al.* (2015)
	Thrips	*Frankliniella schultzei*	Karnataka	Hegde *et al.* (2020)
		Frankliniella spp.	Himachal Pradesh	Vashisth (2009)
		Haplothrips gowdeyi	Karnataka	Hegde *et al.* (2020)
		Microcephalothrips abdominalis	Karnataka	Hegde *et al.* (2020)
		Scirtothrips dorsalis	Karnataka	Rani and Reddy (2001); Jhanshi and Sridhar (2003); Jhanshi and Sridhar (2003); Hegde (2010); Jagdish and Purnima (2011); Sridhar and Naik (2015)
		Thrips hawaiiensis	Karnataka	Hegde *et al.* (2020)
	Whiteflies	*Bemesia tabaci*	Haryana	Yele *et al.* (2020)
		Trialeurodes vaporariorum	Karnataka	Hegde *et al.* (2020)

Insect and non-insect pests associated with fruit crops

The arthropod-pests of fruit crops grown under protected cultivation comprise four groups (Table 10.3) with mites having the higher infestation on fruit crops as compared to other pests. Three mite species were more prevalent in northern regions infesting the temperate crops. Two species of mealybugs associated with guava and grapevine are widely prevalent in southern regions. In north region one species each of aphid, beetle and thrips was found infesting strawberry. Single species of mite was found on apple seedlings under protected cultivation.

Table 10.3. Insect and mite pests of fruit crops under protected cultivation in India

Crops	Pest groups	Scientific name	State(s)	References
Apple Seedlings	Mites	*Panonychus ulmi*	Himachal Pradesh	Ghongade and Sood (2018)
Grapevine	Mealy-bugs	*Planococcus citri*	Karnataka	Mani (2008)
Guava	Mealy-bugs	*Ferrissa virgata*	Karnataka	Mani (2008)
Strawberry	Aphids	*Myzus escalonicus*	New Delhi	Singh *et al. (*2003); Singh *et al.* (2012)
	Beetles	*Harpalus rufipes*	New Delhi	Singh *et al*. (2003); Singh *et al. (*2012)
	Mites	*Eutetranychus* sp.	Himachal Pradesh	Ghongade and Sood (2018)
		Stenotarsonemus fragariae	New Delhi	Singh *et al.* (2003); Singh *et al.* (2012)
		Thrips atratus	New Delhi	Singh *et al.* (2003); Singh *et al.* (2012)

Biological control agents of insect and non-insect pests under protected cultivation

Natural enemies of insect-pests and diseases are known as biological control agents, which include predators, parasitoids and pathogens. They are farmer friendly and can be reproduced easily on a large scale. They usually feed on or all the stages like egg, larvae and adults of the insect pests. A perusal of Table 10.4 and 10.5 showed that majority of the parasitoids belonged to order Hymenoptera, with high prevalence from family Aphelinidae followed by Braconidae. *Aphelinus asychis* was the most common parasitoid under polyhouse conditions in Himachal Pradesh. *Encarsia formosa*, an efficient hymenopteran parastoid of *Trialeurodesvaprarirum*, with high parasitisation rate, can be effectively be utilized in greenhouse whitefly management programme under protected environment (Deeksha, 2020). In case of predators recorded under polyhouse conditions, order Mesostigmata was the highest followed by Hemiptera, Diptera, Araneae, Neuroptera and Coleoptera which were equally and eventually distrsibuted. Among the pathogens, order Hypocreales was the predominant followed by Caudovirales, Baciilaceae, Rhabditida and Pseudomonales and all were equally distributed. In order Hypocreales, family Cordycipitaceae was the most prevalent followed by Clavicipitaceae and Ophiocordycipitaceae. Under family Cordycipitaceae, *Lecanicilium lecanii* was the most effective followed by *Beauveria bassiana* against different species of insect and mite pests in various regions of the country.

Table 10.4. Natural enemies associated with insect and non-insect pests under protected environment in India

Natural enemy/ Host insect	Scientific name	Family/ Order	State(s)	References(s)
Myzus persicae	*Aphelinus asychis**	Aphelinidae, Hymenoptera	Himachal Pradesh	Gavkare *et al.* (2014), Sharma (2015), Verma *et al.* (2018)
	*Aphidius matricariae**	Braconidae, Hymenoptera	Himachal Pradesh	Gavkare *et al.* (2014), Sharma (2015)
	*Aphidius. ervi **	Braconidae, Hymenoptera	Himachal Pradesh	Gavkare *et al.* (2014), Sharma (2015)
	*Diaretella rapae**	Braconidae, Hymenoptera	Punjab	Saloni (2018)
Trialeurodes vaporariorum	*Encarsia formosa**	Aphelinidae, Hymenoptera	Himachal Pradesh	Singh and Sood (2018) Deeksha (2020
	*Encarsia sophia**	Aphelinidae, Hymenoptera	Himachal Pradesh	Kumar and Gupta (2006), Reecha (2010)
	*Encarsia inaron**	Aphelinidae, Hymenoptera	Himachal Pradesh	Reecha (2010)
	Eretmocerus spp.*	Aphelinidae, Hymenoptera	Himachal Pradesh	Kumar and Gupta (2006)
	*Eretmocerus delhiensis**	Aphelinidae, Hymenoptera	Himachal Pradesh	Reecha (2010)
Tuta absoluta	*Trichogramma achaeae**, Trichogramma pretiosum**, Trichogramma chilonis** Trichogramma pieridis***	Trichogrammatidae Hymenoptera	Himachal Pradesh	Manohar *et al. (*2019)
Predators				
Polyphagotar sonemus latus	*Amblyseius tetranychivorus** *Neoseiulus longispinosus***	Acarina, Phytoseiidae Phytoseiidae, Mesostigmata	Karnataka Punjab, Himachal Pradesh, Kerala	Reddy and Kumar (2006) Chauhan *et al.* (2011), Saloni (2018), Lenin & Bhaskar (2019)
Tetranychus urticae	*Neoseiulus longispinosus***	Phytoseiidae, Mesostigmata	Punjab, Himachal Pradesh, Kerala	Chauhan *et al.* (2011), Saloni (2018), Lenin and Bhaskar (2019)
	*Blaptostethus Pallescens***	Anthocoridae, Hemiptera	Punjab	Kaur *et al*. (2019), Ghongade *et al*. (2022)
	*Chrysoperla carnea***	Chrysopidae, Neuroptera	Maharashtra, Himachal Pradesh, Jammu & Kashmir	Kumar and Gupta (2006), Patke *et al.* (2015), Khan *et al.* (2020)
Tuta absoluta	*Nesidiocoris tenuis**	Miridae, Hemiptera	Himachal Pradesh, Karnataka	Varshney & Ballal (2017), Choudhary (2018)
Bemisia tabaci	*Chrysoperla zastrowi sillemi***	Chrysopidae, Neuroptera	Punjab	Ghongade (2020), Khan *et al*. (2020)
Myzus persicae	*Episyrphus balteatus**	Syrphidae, Diptera	Himachal Pradesh	Sharma (2015)
	*Metasyrphus corollae**	Syrphidae, Diptera	Himachal Pradesh	Sharma (2015)
	*Ischiodon scutellaris**	Syrphidae, Diptera	Himachal Pradesh	Sharma (2015)

	*Scaeva pyrastri**	Syrphidae, Diptera	Himachal Pradesh	Sharma (2015)
	*Coccinella septempunctata**	Coccinellidae, Coleoptera	Jammu and Kashmir	Khan *et al*. (2020)
Trialeurodes	*Coccinella septempunctata**	Coccinellidae, Coleoptera	Himachal Pradesh	Kumar and Gupta (2006)
	*Serangium montazerii**	Coccinellidae, Coleoptera	Himachal Pradesh	Kumar and Gupta (2006)
	*Chrysoperla carnea***	Chrysopidae, Neuroptera	Maharashtra, Himachal Pradesh	Kumar and Gupta (2006), Patke *et al.* (2015),
	Argiope pulchella Thorell*	Araneidae, Araneae	Kerala	Thamilarasin (2016)
	Coccinella sp.*	Coccinellidae, Coleoptera	Kerala	Thamilarasin (2016)
	Oxyopes javanus Thorell*	Oxyopidae, Araneae	Kerala	Thamilarasin (2016)
	Oxyopes sunandae Tikader*	Oxyopidae, Araneae	Kerala	Thamilarasin (2016)

*Naturally recorded, ** artificially used

Table 10.5 Entomopathogens associated with insect and non-insect pests under protected environment in India

Scientific name	Family/ Order	Host insect	State(s)	Reference(s)
*Beauvaria bassiana***	Cordycipitaceae, Hypocreales	*Amrasca biguttula biguttula* Ishida*,* *Aphis gossypii, Bemisia tabaci, Meconellicoccus hirsutus, Scirtothrips dorsalis, Liriomyza trifolii,Myzus persicae, Spodoptera frugiperda, Tetranychus neocaledonicus, Trialeurodes vaporariorum*	Himachal Pradesh, Punjab, Uttarakhand, Maharashtra, Rajasthan, Haryana, Karnataka	Sood *et al.* (2003), Kumar (2014), Patke *et al.* (2015), Manju *et al.* (2016), Banshiwal *et al.* (2018), Saloni (2018), Sain *et al.* (2019), Ebadah*et al*. (2020), Singh and Joshi (2020), Halder *et al.* (2021), Idrees et al. (2021); Ghongade and Sangha (2020),
*Lecanicillium lecanii***	Cordycipitaceae, Hypocreales	*Amrasca biguttula biguttula* Ishida*,* *Tetranychus urticae Polyphagotarso nemus latus, B. tabaci, L. trifolii, Tetranychus* spp., *Myzus persicae, Meconellicoccus hirsutus Scirtothrips dorsalis, Tetranychus neocaledonicus* Zacher,	Maharashtra, Punjab Karnataka, Kerala, Himachal Pradesh	Reddy and Kumar (2006),Patke *et al.* (2015), Smitha *et al.* (2017), Chauhan *et al.* (2011), Sharma (2015), Manju *et al.* (2016), Saloni (2018), Sruthi *et al.* (2018), Mirala & Gopali (2019), Singh and Joshi (2020), Halder *et al.* (2021); Ghongade and Sangha (2020)
*Metarhizium anesoplea***	Clavicipitaceae, Hypocreales	*Amrasca biguttula biguttula* Ishida*,*	Karnataka, Haryana Punjab,	Jagdish & Purnima (2011), Kumar (2014), Sain *et al.*

		Myzus persicae, P. latus, Aphis gossypii, S. oblique, S. dorsalis, Bemisia. tabaci, Tetranychus neocaledonicus Zacher	Uttarakhand	(2019), Ebadah *et al*. (2020), Singh and Joshi (2020), Halder *et al.* (2021); Ghongade and Sangha (2020)
*Fusarium semitectum***	Nectriaceae, Hypocreales	*Aphis gossypii, Amrasca biguttula biguttula* Ishida	Karnataka	Jayasimha *et al.* (2012)
*Fusarium verticillioides***	Nectriaceae, Hypocreales	*Tetranychus urticae*	Gujarat	Patel and Ghetiya (2019)
GV_{PTM**}	Baculoviridae, Caudovirales	*Phthorimaeo percullela*	Himachal Pradesh	Thakur and Chandla (2013)
Bacillus thuringiensis (Btk)**	Bacillales, Bacillaceae	*P. opercullela*	Himachal Pradesh	Thakur and Chandla (2013)
*Heterorhabditis indica***	Heterorhabditidae, Rhabditida	*Scirtothrips dorsalis*	Karnataka	Jagdish & Purnima (2011)
*Pseudomonas fluorescens***	Pseudomonadaceae Pseudomonadales	*S. dorsalis* & *P. latus*	Karnataka	Sruthi *et al.* (2018)
*Pacilomyces lilacinum***	Ophiocordycipitac-eae, Hypocreales	*T. urticae*	Karnataka	Manju *et al.* (2016)

*Naturally recorded, ** artificially used

Conclusion

Owing to globalization of markets, shrinking land resource and climate change, protected cultivation of high value crops has emerged as the single most important technology for ensuring high productivity, improved quality and lucrative returns. Based on the insight of available literature it is apparent that amongst the pests associated with crops under protected environment, aphids (*Aphis gossypii*, *Myzus persicae*), mites (*Tetranychus* spp., *Polyphagotarsonemus latus),* tomato pin worm (*Tuta absoluta*), whiteflies (*Bemisia tabaci*, *Trialeurodes vaporariorum)* are of great significance. Many natural enemies involving bio-control agents (predators and parasitoids) microbial pathogen (*Beauvaria bassiana*, *Metarhizium anesoplea*) were found to be associated with these pests, which helps in successful management of greenhouse pests and were safer to non-target organisms.

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11. DIAGNOSIS OF INSECT AND MITE PROBLEMS IN CROPS UNDER PROTECTED ENVIRONMENT

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Abstract: Correct diagnosis of the pest problems is an important prerequisite in the development and implementation of effective pest management strategies. Diagnosis of major insect and mite problems in greenhouse crops is mainly based on the morphology and bio-ecology of the pests as well as on the symptoms due to their damage on the infested plants. Major groups of insect-pests infesting various crops under greenhouse environment include aphids, whiteflies, mealybugs, leaf miners, thrips and caterpillars. Among plant parasitic mites, bulb mite, broad mite, cyclamen mite, tomato rusette mite and two spotted spider mite are the important pests of these crops. Detailed account of prominent morphological features, biological traits and nature of damage of important species of major groups of insect and mite pests of greenhouse crops has been given in this chapter.

Introduction

Correct diagnosis of the pest problem is the key for any effective pest management programme under open field situations or protected environment. It requires comprehensive knowledge about the taxonomic identity of the pest(s), its morphological and bio-ecological aspects, seasonal activity, nature of damage and the characteristic symptoms manifested on infested plants. Number of insect and mite pest species, belonging to different groups, have been reported to infest various crops under protected cultivation and their nature of damage and bioecology needs to be studied for their successful management. Diagnosis of major insect-pests and mite problems in greenhouse crops is mainly based on the morphology and bioecology of the pests as well as their nature of damage or damage symptoms produced on the infested plants. Important diagnostic features of major groups of insect and mite pests are being discussed hereunder:

1. Aphids (Hemiptera: Aphididae):

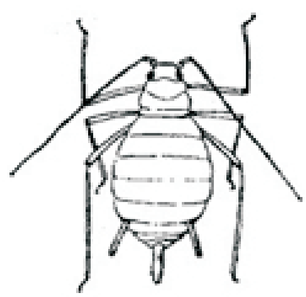

Fig. 11.1: Aphid

Important aphid species comprise green peach aphid (*Myzus persicae),c*hrysanthemum aphid (*Macrosiphoniella sanborni),* cotton or melon aphid (*Aphis gossypii), p*otato aphid (*Macrosiphum euphorbiae)* and *r*ose aphid (*Macrosiphum rosae)*. Most aphids are 2-3 mm long soft bodied insects having pear shaped bodies with paired tube-like structures called cornicles protruding from the back end (Fig. 11.1). They may be winged and wingless and vary in colours from green to brown, yellowish, red, black etc. Green peach aphid is yellowish green in summer and pink to red in autumn and spring, cotton aphid is green, yellow, and blackish, and chrysanthemum aphid has maroon or dark brown forms.

Aphids reproduce parthenogenetically and each female gives birth to 60-100 nymphs in 20-30 days which mature within a week. Winged females are produced under unfavourable conditions. Males and eggs are produced only in very colder regions where, the egg is the overwintering stage. There may be several generations in a year and under protected cultivation they continue to develop the year-round. Aphids cause damage by sucking cell sap from the leaves, buds and stems by inserting their needle like stylets (mouth parts) into phloem tissues. Symptoms of damage are manifested as chlorotic spots, distorted leaves, stunting and/or wilting, reduction in productivity and plant vigour. Aphids secrete honey dew, which drips into plant foliage resulting into development of sooty mould, hampering photosynthetic activity. Some aphid species eg. *M.persicae*, are responsible for the transmission of plant viruses. Aphid infestation may be monitored by checking the lower leaves, around the terminals or flower buds and on the top 6 inches of the stems of the older plants. Cast skins (exuviae), honeydew droplets (presence of ants) and sooty mould are indication of infestations. Often localized infestations are seen.

2. Whiteflies (Hemiptera: Aleyrodidae)

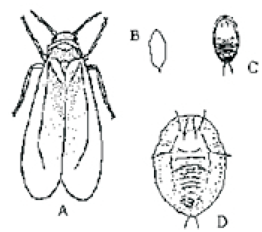

Fig. 11.2: Different stages of whitefly (A-adult, B-egg, C-crawler, D-pupa)

Greenhouse whitefly (GHW) (*Trialeurodes vaporariorum), s*weet potato whitefly (*Bemisia tabaci),s*ilver leaf whitefly (*B. argentifolia),* banded wing whitefly (*T. abutilonea)*are the important species of whiteflies infesting greenhouse crops. Adult whiteflies are about 1-3 mm long, covered with a white waxy powder (Fig. 11.2). Greenhouse whitefly hold their wings flat over the abdomen. Sweet potato and silver leaf whiteflies hold their wings roof like and close to the sides of the abdomen. The banded wing whiteflies have light grey bars across the wings. Adults of all these species congregate on the underside of leaves usually at the top of the plant. GHW lays 6-20 cigar shaped eggs daily in a perfect circle or part of the circle on the underside of the leaf. In case of sweet potato whitefly, eggs are randomly laid in small groups or singly. Eggs hatch in 7-10 days and the 'crawlers', mobile first instar nymphs of whitefly, search for suitable place to settle. Next two in-stars are sessile, translucent green or yellow. The fourth instar - pupa, is opaque yellow and mounded. Nymphs and pupae of many species have distinctive white waxy spines but these are not present in *B. tabaci*. GHW pupae are cake shaped with erect side-walls. Sweet potato and silver leaf whitefly pupae are mounded. The damage symptoms caused by whiteflies are the same as in case of aphids. Clear sticky- excessive honeydew and sooty mould can be seen on lower side of the leaves. Their presence reduces the aesthetic value of the plants and some of them are also the vectors of several viral diseases. Early detection of whitefly infestation is very important and can be achieved by using yellow sticky traps and by examining the plants to determine the number of immature individuals. Whiteflies can be seen on relatively young and new tissues and the leaves may be turned over to examine the undersides. Magnifying hand lens (10-15X) may be used for better observing the immature stages. On many crops different species can be observed hence, it is important to correctly diagnose the species.

3. Mealybugs (Hemiptera: Pseudococcidae)

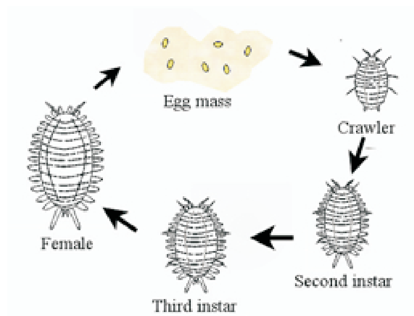

Fig. 11.3: Different stages of mealybug

Important species of mealybugs include longtailed mealybug (*Pseudococcus longispinus), c*itrus mealybug (*Plenococcus citri),* Mexican mealybug (*Phenacoccus gossypii)*, cactus mealybug (*Hypogeococcus festerianus),* obscure mealybug (*Pseudococcus affinis).* Mealy bugs are pink soft bodied insects covered with waxy, cottony material (Fig. 11.3). Citrus mealy bug females are wingless, 1-3 mm long and lay up to 600 small yellow coloured eggs within a protective mass of white, cottony threads. The long tailed mealybugs don't lay eggs but give birth to live young ones. After producing eggs or young ones over a period of 5-10 days, the females die. The immature insects search for feeding sites. Male nymphs settle and spin an elongated waxy cocoon. Females have three instars and are mobile throughout their life. Adult males are tiny and winged. One generation takes 1-3 months and feed on the above ground plant parts i.e. stems, tips, leaf junctures and new growth and some are root feeders. Stunting, defoliation, yellowing and wilting are the characteristic symptoms. Plant may be malformed due to toxin production by citrus mealy bug and sooty mould may be observed on honeydew. For diagnosing their infestation, visual inspection for white cotton like masses of waxy threads on leaves and stems, and long tailed in leaf whorls is an important visual diagnostic prominent feature for their infestation. Presence of ants, wasps or bees also indicates the infestation. A small white cottony mass around the drainage holes of the pots is the indication for underground infestation.

4. Thrips (Thysanoptera: Thripidae)

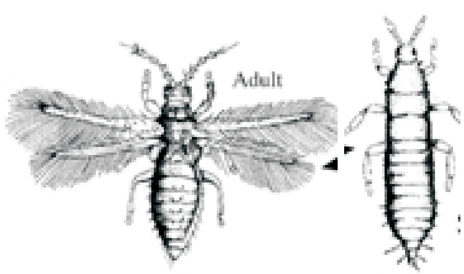

Fig. 11.4: Thrips (adult and larva)

Important species of thrips are western flower thrips (*Frankliniella occidentalis),* onion thrips (*Thrips tabaci), c*hili thrips (*Scirtothrips dorsalis), e*astern flower thrips *(Heliothrips haemorrhoidalis) and* melon thrips (*Thrips palmi)*. An invasive species, *T. parvispinus* was first reported on papaya in South India during 2015. It inflicts damage to several ornamental and vegetable crops under field conditions. Thrips are relatively small, mostly1-2mm long (Fig.4). Wings may be present or absent and in case wings are present, these are unique i.e. narrow, with few or no veins, fringed with long hairs. They are slender, pale to blackish in colour. Thrips have asymmetrical mouthparts; right mandibles are reduced or vestigial or completely absent in some species. Thrips reproduce the year-round with 12-15 generations per year. Females lay 600-1000 eggs during the life period which are inserted through the holes cut into leaves, flower buds or fruit tissue with saw like ovipositor. Eggs hatch in 2-7 days and nymph feeds for two instars and then passes through the non-feeding pseudopupal stages (prepupa and pupa) in protected parts of the plant (leaves/flower), in litter or soil. Thrip nymphs are often referred to as larvae. Thrips don't feed or move unless disturbed during the 2-5 day 'pupal' stage.

They puncture the plant surface and feed on the exuded sap from the resulting wound. Injury is also caused while the females lay eggs. The prominent symptoms are manifested as white or silver specks on the leaf, flower petals or fruits which are arranged in streaks rather than the stipples caused by mites. These spots dry up, turn tan or brown on some plants. Thrips enter the flowers at the bud stage leading to damaged blossoms which turn brown or the buds fail to open completely. Petals become distorted, develop brown edges and stick together. Thrips excrete brown droplets during feeding on petals and leaves which turn into black spots on drying. Heavy infestation of thrips leads to deformities in the new leaves, flowers and fruits. Early visual detection of thrips is difficult and yellow or blue sticky traps are most useful for detecting first infestation. A combination of sticky traps, blowing CO_2 into flowers, and flower monitoring are important practices for quick detection of thrips.

5. Caterpillars (Lepidoptera)

Fig. 11.5. Caterpillar

Caterpillars belong to different families of the order Lepidoptera. Important species of caterpillars include: armyworms (*Spodoptera litura* and *S. exigua),* tomato fruit borer (*Helicoverpa armigera)*, tomato pin worm (*Tuta absoluta)*, cutworm (*Agrotis ipsilon), diamondback moth* (*Plutella xylostella)* and brinjal shoot and fruit borer (*Leucinodes orbonalis)*. The adults of caterpillers are called moths which are nocturnal and female moths lay eggs on plants. Caterpillars (Fig. 11.5), the immature stages, cause damage by feeding on the underside of the leaves for several days. Larger caterpillars eat throughout the whole leaf, fruits or flowers. Caterpillars can grow to two inches in length, chew off foliage and the plants appear ragged in appearance. Some species directly feed on flowers and fruits. Damaged buds don't produce auxiliary shoots instead of flowers. Excreta of caterpillars deteriorate quality of the produce.

Light traps/ pheromone traps should be used for early detection of moths. Small green fecal pellets near chewed foliage often indicate a caterpillar attack. Check for the presence of egg masses or single eggs and young caterpillars.

6. Leaf miners (Diptera: Agromyzidae)

Fig. 11.6 : Leaf miner (adult fly and maggot with leaf mine)

Several species of serpentine leaf miner viz. *Liriomyza trifoli*, *L. sativae,L. huidobrensis*, *L. brgoniae* and the pea leaf miner (*Chromatomyia horticola)*are the important pests (Fig. 11.6). The adults of *L. trifolii*, the most important species of leaf miners under protected cultivation, are small, black yellow flies with their wing length varying from 1.25-1.9mm. The area of head behind the eyes is mostly yellow whereas, the portion behind the eyes is black. Larvae of leaf miners are called maggots which are the damaging stages. These make tunnel within the leaves between the upper and lower surfaces and feed within, making white blotches or twisting lines (tunnels). Adult females also cause numerous punctures on the leaves. Punctures and mines interfere with the photosynthetic activity and thus reduce the crop yield. Young seedlings are completely destroyed and infestations in ornamentals reduce their market value. In case of bacterial leaf spot in chrysanthemum, bacteria get entry through the puncture made by the females of leaf miners whereas, in tomato, shedding of leaves above the fruits due to infestations make them vulnerable to sunburn.
Use yellow sticky traps to detect adults in the greenhouses and examine the plants for presence of white mines with larvae within. Damage of the first generation may be masked by new foliage in fast growing crops until the second generation attacks the new upper leaves. The leaves should be sampled randomly at weekly interval to estimate larval population.

7. Mite (Acari) Pests

Following mite species are the important and infest various crops grown under protected cultivation:

i) Two spotted spider mite, *Tetranychus urticae* and *T. cinnabarinus* (Family: Tetranichidae)
ii) Broad mite, *Polyphagotarsonemus latus* (Family: Tarsonemidae)
iii) Cyclamen mite, *Phytonemus pallidus* (Family: Tarsonemidae)
iv) Tomato rusette mite, *Aculops lycopersici* (Family: Europhidae)

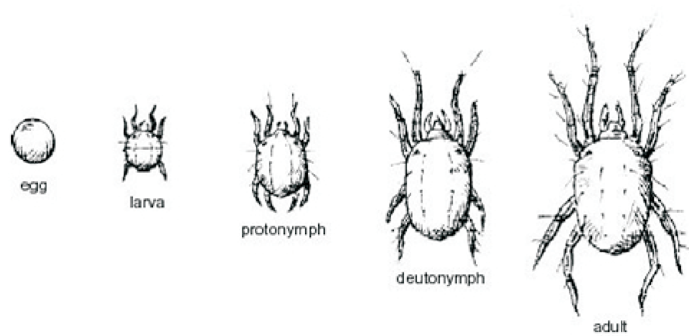

Fig. 11.7: Different life stages of mites

i) Spider mites:

These are small mites (0.5 mm long), light yellow to green or dark green or brown in colour (Fig.11.7) with two black spots on the abdomen. Males are smaller and thinner than the females. Each female lays up to 120 white and perfectly spherical eggs in webbing on the underside of the leaves. Eggs hatch into larvae in 4 to 6 days which are small and white with only six legs and moult into 8-legged nymphs. Adults appear after 2^{nd} nymphal stage. Generation time varies from 7-10 and >40 days in warm and cooler temperatures, respectively. The mites undergo diapause for several months in severe winter.
The mites feed on the underside of the leaves removing cell contents leading into chlorotic stippled appearance on the leaves which dry out and falloff. Large population can kill plants. Webbing can cover foliage and flowers. Quality of flower and yield is reduced. Carmine mites don't produce typical speckling of leaves but they become prematurely chlorotic with small transparent lesions. Bright yellow patches develop that turn dark and spread over the entire leaf. Frequent visual observations on symptomatic plant parts are important to diagnose their problem. However, these are often

overlooked until their feeding damage or webbing is apparent. These can be found all over the plant, most often on older, middle-age leaves and midrib. Some 'indicator plants' (radish and limabean) can be used to detect small populations.

ii) Tarsonemid mites:

Tarsonemid mites include broad mite and cyclamen mite. These are very small (0.2 mm long) and light yellow to amber in colour. The adult cyclamen mite is semi transparent and pinkish orange. The immature stages are translucent. The adults of broad mite adults are straw coloured with a prominent white stripe down the centre of back and 0.3mm long. Cyclamen and broad mites lay eggs on upper and underside leaves, respectively. Eggs hatch in 2-7 days into whitish larvae which pass through an inactive nymphal stage before moulting into adults. Leaf distortion, stunting, bronzing and plant death are the common symptoms of the damage which resemble pesticide injury or nutritional disorders. Flowers become distorted or may not open. Fruits on tomato, cucumber, pepper may be russetted or distorted.

Frequent visual observations on symptomatic plant parts are required. Generally, mites avoid light and prefer high RH and tend to be found in the crown of their hosts. Cyclamen mite usually remains within buds whereas, broad mite on the more exposed surfaces. Microscopic observation is necessary to confirm their presence

iii) Eriophid mite (Tomato russett mite):

It is wormlike mite which is very small in size (0.2mm). It destroys epidermal cells of leaflets resulting in curling of leaflet edges. Symptoms of damage are- rusting of damaged tissues, desiccation and plant death.

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12. ROLE OF BIOLOGICAL CONTROL AGENTS FOR THE MANAGEMENT OF INSECT AND MITE PESTS UNDER PROTECTED CULTIVATION

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Abstract: Insect and mite pests are a big challenge in protected cultivation. Continuous and indiscriminate use of insecticides may lead to resistance and other problems whereas, biological control is ecofriendly and sustainable approach. In European countries many biocontrol agents are being used in protected cultivation to target different pests. In India also, many biocontrol agents have proven their effectiveness against many insect pests *viz*, whitefly, thrips, mites and aphid etc. There is need to explore the effective biocontrol agents and conductive trials to understand their efficacy in protected cultivation and to make the effective biocontrol agents available to farmers at right time to achieve success and to get pesticide free produce.

Inroduction

In the past 24 years the surface areas with greenhouses have increased by more than 80%, with an increase of 4.4% per year (Bueno, 2005). Asian, Mediterranean and Latin American countries showed a strong increase in protected areas stimulated by cultivation of high-value crops. In India, total cumulative area brought under protected cultivation under NHM was estimated to be 2.15 lakh ha during 2017-18 which is mainly confined to Andhra Pradesh, Maharashtra, Karnataka, Himachal Pradesh, Punjab, Haryana and Rajasthan.

In protected cultivation managing pests is challenging proposition as it develops resistance against many chemicals because of their excessive use to maintain low insect pressure. Greenhouse conditions are conducive for fast multiplication of insect pests due to availability of continuous host plants. Use of biological control agents as alternative of chemical control is a viable option to manage these insect pests. Major Insect and mitepests associated with crops grown under protected environment are given in Table 12.1.

Whiteflies and their natural enemies

Whiteflies are one of the major pests in the greenhouse. Two species of whitefly *viz*., *Trialeurodes vaporariorum* (Westwood 1856) and *Bemisia tabaci* (Gennadius) are the serious pests. Usually, they inhabit lower surface of leaves and on disturbance of plant they flutter from the undersides of leaves. The female of these sap-sucking insects may lay upto 150 eggs @ 25 per day. The entire life cycle takes 21-36 days, depending on the greenhouse environment. They can complete more than 12 generations in a year.

Both the nymphs and adults of whitefly feed on phloem cell sap and cause chlorotic spots. The leaves dry-up prematurely and plant growth is affected. Nymphs also secrete honeydew, which covers leaf surfaces and flowers on which the sooty growth develops under humid weather conditions.

In India, natural enemies viz*, Encarsia inaron, E. formosa, E. sophia, Eretmocerus* spp., *Coccinella septempunctata, Serangium haleemae, S. montazerii, Chrysoperla zastrowii sillemi* and *Amblyseius* (*Euseius*) *delhiensis* have been reported on *T. vaporariorum* (Singh et al., 2017)

Following parasitoids are used against whitefly worldwide:

***Encarsia formosa*:** The use of parasitoid as a biological control agent is considered to be one of the biggest success stories in greenhouse biological control (van Lenteren et al., 2000). During 1930s this parasitoid was sent to various parts of Europe, Canada, Australia and New Zealand. By 1996, 20 out of 35 countries with greenhouse industry were using *E. formosa*. *Encarsia formosa* is a solitary endoparasitoid that matures 8-10 eggs per day. It oviposits in all immature stages of *T. vaporariorum*, except the egg and the mobile first instar, and in all immature stages of *B. tabaci*.

Table 12.1 Major Insect and mitepests associated with crops grown under protected environment:

Group	Insect and mite pests	Host	Distribution
Aphids	*Aphis gossypii*	Capsicum	New Delhi, Punjab
	Macrosiphoniella sanborni	Chrysanthemum	Himachal Pradesh, Karnataka
	Macrosiphum luteum	Orchids	Sikkim
	Myzus escalonicus	Strawberry	New Delhi
	Myzus persicae	Capsicum, gerbera	Maharashtra, Punjab
	Toxoptera aurantii	Orchid	Sikkim
Caterpillars	*Helicoverpa armigera*	Capsicum, carnation, tomato	Himachal Pradesh, Punjab, Uttrakhand
	Spodoptera litura	Capsicum, cucumber rose, tomato	Himachal Pradesh, Karnataka, Punjab
Leaf-miner	*Liriomyza trifolii*	Cucumber, chrysanthemum, gerbera, tomato and many ornamentals	Himachal Pradesh, Karnataka
Mites	*Polyphagotarsonemus latus*	Capsicum	Himachal Pradesh, Karnataka, New Delhi, Punjab
	Stenotarsonemus fragariae	Strawberry	New Delhi
	Tetranychus cinnabarinus	Carnation	Maharashtra
	Tetranychus neocalidonicus	Cucumber	New Delhi
	Tetranychus urticae	Capsicum, carnation, cucumber, gerbera, tomato	Himachal Pradesh, Kerala, Maharashtra
	Tetranychus truncatus	Capsicum, cucumber, tomato, pumpkin	Kerala, Maharashtra
Thrips	*Thrips palmi*	Gerbera	Karnataka
	Thrips tabaci	Gerbera	Maharashtra
Whiteflies	*Bemisia tabaci*	Gerbera, capsicum	Karnataka, Pumjab
	Trialeurodes vaporariorum	Capsicum, cucumber, French beans, gerbera, tomato and more than 30 hosts	Himachal Pradesh, Tamil Nadu (Nilgiri hills)
	Aleurothrixus trachoides	Brinjal, chilli, duranta tomato	Karnataka, Kerala, Maharashtra, Tamil Nadu

Source: Sood (2010); Sood et al. (2018) and Rathi et al. (2018)

Eretmocerus eremicus: *Eretmocerus eremicus* is indigenous to the southern desert areas of California and Arizona (Rose and Zolnerowich, 1997) and is an important parasitoid of whiteflies in these areas. The optimum temperature for its rapid development and egg production is 25-29°C. Three females /plant/week results in >98% mortality of silverleaf whitefly in the first 6-8 weeks of the poinsettia crop. Parasitoid is supplied as pupae protected in their host whitefly scales (pupae) or loose in a bottle with bran flakes which can be distributed throughout the crop, plain without the bran, and in blister-pack hanging cards.

Eretmocerus mundus: It is a solitary ecto- endo- parasitoid of whitefly nymphs (Rose *et al.* 1996). This parasitoid lays eggs under the whitefly nymph and the first instar larva penetrate the host. Though this parasitoid can attack all the whitefly instars, but it prefers the second instar (Jones and Greenberg 1998). In Spain, this parasitoid proved to be effective against *B. tabaci* in greenhouse tomatoes (Arno *et al.* 2005).

Aphids and their natural enemies

Aphids are small and soft-bodied insects. They suck the cell sap from leaf or apical growing parts and prefer to feed on tender, young growth. Aphids multiply at rapid pace completing one generation in 7-10 days. Feeding by aphids can cause leaves or stems to curl or pucker and this leaf distortion often protects the aphids from contact insecticides. They also act as vector of many viral diseases.
The aphid species, *Myzus persicae* and *Aphis gossypii* are the most damaging insect pests of crops grown under protected conditions across the world because of their ability to transmit viruses to the plants. *Myzus persicae* causes 19.4% yield loss on vegetable crops under protected cultivation in India (Singh and Joshi 2020). However, on an average, damage caused by insect pests under protected conditions on various crops ranges from 15-37%. In India, *M. persicae* is recorded in various regions of Punjab, Himachal Pradesh and Maharastra on capsicum, cucumber, tomato and gerbera.
Following natural enemies are being used worldwide against aphids:

Aphidius colemani is widely used in biological control programmes against *A. gossypii* on eggplant and cucumber. It can parasitize all the instars of *M. persicae* and *A. gossypii*.

Aphelinus abdominalis is used against *M. euphorbiae* in greenhouses (Holler and Haardt 1993).

Besides, above mentioned parasitoids there are some predators effective against aphids. Predatory midges, belonging to the family Cecidomyiidae, are highly polyphagous species. *Aphidoletes aphidimyza* Rondani is effective against *M. persicae* on tomato, egg- plant and sweet pepper (Meadow *et al.* 1985). This is the only aphid predator produced on a wide scale.
Macrolophus melanotoma (previously named *M. caliginosus*) is also found feeding on *M. persicae*, *M. euphorbiae* and *A. gossypii* (Alvarado *et al.* 1997). *Dicyphus tamaninii* was reported to cause impact on the population densities of *A. gossypii* due to its high consumption rate on *A. gossypii* (Sengonca and Saleh 2002).
In addition, the predatory bugs *Anthocoris nemorum* (L.) and *A. nemoralis* (Hemiptera: Anthocoridae) showed potential as biological control agents of *M. persicae* (Meyling *et al.* 2003).
In Himachal Pradesh, *Chrysoperla zastrowi sillemi* (4 larvae/ plant) resulted in maximum reduction (55.8%) in aphid population in capsicum over control and was at par with *Lecanicillium lecanii* (50.3%) and azadirachtin (49.8%) (AICRP-BC report 2017-18)

Thrips and their natural enemies

Thrips are tiny, slender insects about 1-1.5 mm long. They have four fringed wings with a row of long hairs that are held flat over their back. Female thrips insert eggs into slits in the tissue. Eggs hatch in 2-7 days and the nymphs feed just like adults and molt four times during development. They pupate in debris or soil.
Thrips infest the leaves, flowers, buds and young fruits of a crop. They feed by rasping the plant surface and sucking up the exuding sap. Heavily infested leaves have a mottled or silvery appearance.
In protected cultivation, predatory mites, hemipetran bugs, entomopathogenic nematode and fungi have been reported to control thrips.

***Amblyseius swirski**,* a predatory mite has shown its effectiveness against *Frankliniella occidentalis* (van Houten *et al.* 2005). It was introduced to the market in 2005 for the control of thrips (Bolckmans 2005). This species can control thrips and whiteflies simultaneously.

Predatory bugs are the major biocontrol agents against thrips in greenhouse. The most important of these predators are the species of the genus *Orius* (Hemiptera: Anthocoridae). They are mostly found in flowers and share niche with thrips and thus help in controlling thrips.

In India, *Blaptostethus pallescens* has been reported to be effective against thrips. *Pseudomonas fluorescens* strain NBAIR-PFDWD and *Bacillus albus* strain NBAIR-BATP were found effective for

the management of *Thrips* spp. in chilies under polyhouse conditions in Udayapura, Karnataka.
Pseudomonas fluorescens strain NBAIR-PFDWD + Yellow sticky trap (Kairomone)+*Blaptostethus pallescens* (3 releases @ 20 nymphs/m^2) provided 70.0-72.5% reduction in thrips population on capsicu m in Kranataka.
Sprays of *Beauveria bassiana*, *Metarhizium anisopliae* and *Lecanicillium lecanii* (@ $2x10^7$ c.f.u./ml) along with the anthocorid bug (*Blaptostethus pallescens*) @ 20 bugs/plant caused significant reduction of gerbera thrips, *Frankliniella* spp. population and were at par with imidacloprid sprayed treatments in Kerala (AICRP-BC report 2018-19).

Mites and their natural enemies

Mites are sap-sucking pests which attack a wide range of greenhouse plants. Two-spotted spider mite (*Tetranychus urticae)* and the yellow mite (*Polyphagotarsonemus latus*), are the serious pest in greenhouses.
The female of two-spotted spider mite lays 100 to 150 eggs. The pest can complete upto 30 generations in a year. Generally, they feed on the undersides of leaves, giving the upper leaf surface a speckled or mottled appearance. Leaves of mite-infested plants may turn yellow and dry up, and highly infested plants may lose vigour and die.
Yellow mites are minute, elliptical, semi-transparent, greenish mites. Infested leaves become distorted and often curl inward.
Many predatory phytoseiid mites are the most important biocontrol agents for pest mites e.g. specialist predator, *Phytoseiulus persimilis* and the generalist *Neoseiulus californicus* McGregor.
Phytoseiulus persimilis is commonly used against *T. urticae* worldwide on cucumber, tomato and sweet pepper (van Lenteren and Woets 1988). Other phytoseiid mites that have been used in the control of spider mites are *Neoseiulus barkeri* Hughes, *N. fallacis* Garman and *N. californicus.*
In India, Neoseiulus indicus and *Blaptostethus pallescens* have been found effective against broad and spider mites. Besides that, *Hirsutella thompsonii* F.E. Fisher has also been found effective against broad mites on mulberry (Kumar and Varshney, 2020)
Four releases of anthocorid predator, *Blaptostethus pallescens*@ 20 nymphs/ rose plant was effective in suppressing the rose mite population (26.8 mites/5 leaves/plant) in Maharashtra (AICRP-BC Report 2017-18).
Release of predatory mite, *Neoseiulus longispinosus* at predator: prey ratio of 1:30 reduced 71% population of *T. urticae* on carnation and on par with Neem Baan in Himachal Pradesh (AICRP-BC Report 2017-18).

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13. MANAGEMENT OF INSECT AND MITE-PESTS IN PROTECTED AGRICULTURE

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Abstract: Protected cultivation provides stable and congenial micro-environment which is favourable for the multiplication of insect-pests and becomes one of the limiting factors for successful crop production under protected environment. The protected environment provides insect-pests with an enormous food plants in monoculture in the absence of natural regulating factors. Hence, it becomes necessary and the biggest challenges, to detect them in early stage of infestation and diagnose them correctly for their management. There arises a need to improve diagnostic skills of the growers as well as the extension functionaries. Efforts are also needed to reduce sole reliance on chemical pesticides by exploring the potential of associated natural enemies and biopesticides. Also, the initiatives are needed to develop holistic integrated management modules for the pests in different crops.

Introduction

Protected cultivation also known as 'Controlled Environment Agriculture' is the most contemporary approach to produce horticultural crops qualitatively and quantitatively (Jensen 2002). It involves the cultivation of crops in an environment wherein the factors like temperature, relative humidity, soil, water, plant nutrition etc. are manipulated to attain maximum produce. By adopting protected cultivation technology, the growers can look forward to a better and additional remuneration for high quality produce (*Albright 2002;* Sabir and Singh 2013) and is amongst the technologies to double their income.

Protected cultivation provides stable and congenial micro-environment which is favourable for the multiplication of insect-pests and becomes one of the limiting factors for successful crop production under protected environment (van Lenteren 2000; Kaur et al. 2010; Sood 2012). Protected environment provides insect-pests with an unlimited amount of food plants in monoculture in the absence of natural regulating factors.

Mode of entry of insects in protected structures

The insect pests mostly invade the protected structures alongwith infested planting material, from the damaged/torn cladding material, by direct entry through door, with the clothes of workers/ visitors. Sometimes infestation from previous crop or host plants from outside but near the protected structures also acts as source of initial buildup of insect and mite-pests in protected structures.

Management of insect and mite-pests in protected environment

Integrated pest management (IPM) is a decision support system for the selection and use of pest control tactics, singly or in harmoniously coordinated management strategy, based on cost/benefit analyses that take into account the impact on producers, society and the environment (Kogan 1998). Sood (2012) and Reddy (2016) described IPM program for protected cultivation as a pyramid having three key components namely, avoidance, early detection and curative measures (Figure 13.1).

It included "avoidance of pest problem", comprising physical exclusion methods, sanitation, cultural practices, resistant cultivars and biological control agents as the foundation of sustainable IPM programme. The holistic adoption of which can check the entry and build-up of insect-pests under protected environment. "Early detection" is a regular and systematic inspection of crop and exterior by monitoring and scouting to identify and assess pest problems. Whereas, the "curative measures" comprising diagnosis based selective use of pesticides to check the flaring pest populations. An extensive literature survey suggests that pests are being managed under protected environment by adopting these principles. These are being reviewed hereunder:

1. Avoidance

a. Physical exclusion methods

A variety of physical methods based on insect proof screens, double door system, UV radiations, electrostatic exclusion and insect suction devices have been evaluated by researchers for the management of insect-pests under protected cultivation.

Insect-proof screens and double door system: Of all physical exclusion possibilities, only insect exclusion screens and double door system have been widely adopted as they are both environment-friendly and very reliable. The use of screens on vents can exclude certain insect-pests from protected structures and therefore results in reduction of pesticide use on crops. Depending on the target pest, the openings in the screen must clearly be smaller than the size of the insect (Bethke et al. 1994; Hanafi et al. 2007). The screen of 42 and 58 mesh with corresponding porosity of 290 and 462 µm can exclude whitefly species viz. *T. vaporariorum* and *B. tabaci*, respectively (Teitel 2007; Sood 2012). Berlinger et al. (2002) suggested the use of exclusion screens to be an economically viable whitefly management method and reported a wide adoption by tomato growers in Israel. Studies conducted by Sood (2012) in Himachal Pradesh revealed fixing of inappropriate exclusion screen net to be one of the reasons for increased abundance of insect-pests as majority of polyhouses (78.1%) in the state were having inappropriate orifice (21-30 mesh). Also, only a few (20.7%) polyhouses were having provision of double doors. BuKeun et al. (2013) found that 83 mesh net completely prevented the entry of *B. tabaci* in greenhouse cropped with tomato. Cirenio et al. (2014) evaluated five screens with different pore sizes to quantify the presence of *B. tabaci* in exterior and interior of greenhouses cropped with tomato, the incidence was 30 per cent more outside. Mesh with 39 per cent porosity limited the abundance of *B. tabaci* with relatively higher tomato yield. Punjab Agricultural University, Ludhiana also recommends covering all ventilations of the protected structures with net of 40-mesh size and ensuring double-door to prevent insect-pest infestations (PAU 2022).

UV- blocking/ absorbing cladding material: The UV part of the solar/light spectrum plays an important role in the ecological behaviour of insects, including immigration, orientation, navigation, feeding and interaction between the sexes (Raviv and Antignus 2004; Díaz and Fereres 2007; Ben-Yakir and Fereres 2016). The insects have receptors for UV light with peak sensitivity at 360 and 520-540 nm for UV and green-yellow light, respectively. The absence of UV deters pests and decreases their dispersal rate. Nakagaki et al. (1982) reported the first evidence of the inhibitory effect of UV-blocking materials on the invasion of greenhouse by insects. They observed that population of *T. vaporariorum* was lower on tomatoes grown in a plastic house made of polyethylene and treated to exclude UV wavelengths than on crops grown in an ordinary plastic house. Optical manipulation has been found to reduce the infestation levels of whiteflies by 2-10 folds (Ben-Yakir et al. 2014). Similar observations were reported by other workers (Antignus et al. 2001; Mutwiwa et al. 2005; Urbanus et al. 2005; Kumar and Poehling 2006 and Dimitrios and Christopher 2007).

Reducing UV radiation also does not limit the role of beneficial insects like natural enemies and pollinators. Doukas and Payne (2007) confirmed that *Encarsia formosa* dispersal is not affected by the environments with low UV-light while, this wavelength radiation is necessary for their whitefly host flight activity and dispersal. Field tests in the Mediterranean area showed that insect pollination is not affected, provided that enough time is given to the beehives to get accustomed to the low UV levels within the greenhouse (Wilfried et al. 2013). Blocking UV-radiation may have detrimental effects on secondary metabolism like plant defenses and micro-nutritional quality of products (Wilfried et al. 2013; Zhu et al. 2016). However, commercial availability of UV blocking/ absorbing cladding material is still limited.

b. Sanitation

Sanitation is a basic component of cultural practices. Infestations are easier to prevent than to cure. Before introducing a new crop into the greenhouse, it is extremely important to eliminate pests from the previous crop. Remove all plant debris and weeds from the greenhouse (PAU 2022). Many pests also occur on other crops or broadleaf weeds. For this reason, it is important to avoid growing other crops next to the greenhouse and to prevent heavy growth of broadleaf weeds around the outside edges of the greenhouse. A fallow period of two to four weeks reduces the pest load considerably. To determine the presence of insect-pests, set up yellow sticky cards and indicator plants after watering and observe for any insects that are trapped on the cards. Only thereafter the decision regarding plantation of new crop be made.

c. Plant nutrition

The relationship between plant nutrient content and insect populations has invoked the interest of ecologists for a long. Insects need multiple nutrients for their growth and development (Busch and Phelan 1999; Joern et al., 2012). Fertilization practices may also affect crop tolerance to pests by affecting the growth pattern, the anatomy and morphology and particularly the chemical composition (Michaud and Charbonneau 1993). Amongst different group of insects, sucking insects show a much stronger response to crop fertilization (Balakrishnan et al., 2007; Butler et al., 2012).

Nitrogen fertilization showed very clear and significant effect on growth and development of most of the Hemipteran insect-pests (Singh and Sood, 2017; Bala et al. 2018). High N doses result in increased oviposition, abundance and survival of different species of whiteflies. Studies on different aphid species also revealed that high N level enhances weight, size, fecundity, finite rate of increase and low mean generation time. Also, in other hemipterans like leafhoppers, plant hoppers, psyllids, mealy bugs and scale insects a positive correlation between N level and population density, damage to plants, number of individuals, size, egg laying etc. has been observed.

Potassium (K), on the other hand has negative impact on growth and development of sucking pests. Higher K levels results in decline in population, incidence, intrinsic rate of population increase and net reproductive rate of aphids and whiteflies. So, the idea that higher levels of N fertilizers increase the number of pest and K is outstandingly important in conferring 'resistance' to pest attack finds great support.A very few studies of phosphorus and other nutrients on the aspects reviewed have been undertaken and their effects on host plant resistance to sucking pests are less clear. These showed varied effects on different hemipteran groups.

Results of a study conducted by Singh (2017) showed an increase in *T. vaporariorum* nymph population in tomatoes grown under protected environment supplied with a fertilizer dose comprising 200% N and 100% PK of recommended field dose of fertilizer (RFD). Population of the nymphs declined with an increase in K. It remained minimum in treatment comprising 25% NK+ 100%P of RFD but plant growth was affected adversely. The treatments with 150 to 200%K+100%NP of RFD also resulted in a reduced population of the nymphs.

d. Use of natural enemies

Biological control is the action of parasitoids, predators or pathogens in maintaining pest organism population density at a lower level that would occur in their absence. The organism that suppresses the insect pest is referred to as the biological control agent. In Western Europe and North America, the bioagents are commercially available and are being used successfully for the management of pest problems under protected situations. In India, numerous potential BCAs have been recorded from crops grown under protected cultivation (Singh et al. 2017 and Sood et al. 2018). However, this technique though is having limitations like adverse impact of temperature extremes, pesticides, less tolerance of pest damage amongst consumers and lack of a system for supplying natural enemies of good quality under Indian conditions.

2. Early detection

Early detection of pest infestation is a key-point for crop management. In case of whiteflies, it can be achieved by regular monitoring and surveillance by using yellow coloured sticky traps.

a. Yellow attractant traps : Insects use optical cues for host finding, flight orientation and navigation. From a biological perspective, three parameters of colour, namely, hue (dominant wavelength emitted by the surface), purity of colour and brightness (light intensity or overall reflection) are used by insects to distinguish between host and surrounding environment (Vaishampayan et al. 1975; Antignus 2000). Instead of seeing leaves as a green colour, they see varying hues of yellow and blue that is reflected from the leaf surface (Lim and Mainali 2008; Ben-Yakir et al. 2014). Combinations of different colours, shapes, sizes and geometrical designs of sticky traps have shown interesting visual reactions in whiteflies. In past, numerous studies have been undertaken to evaluate yellow colour in combination with different traps, sticky materials and their placement. Singh and Sood (2020) found low cost yellow paper traps smeared with castor/ mustard oil good in efficacy and also cost effective in management of greenhouse whiteflies in tomato.

b. Light traps: The IIHR scientists developed the effective package for the control of *Tuta* comprising use of incandescent bulb @ one bulb/150 m^2 + 1 pheromone trap/300 m^2 and need based spray of spinosad 0.25 ml/l or flubendiamide @ 0.20 ml/l at 3 weeks of interval. Coinciding with the peak emergence of the *Tuta* adults, spray of deltamethrin 2.5 EC @ 1 ml/l for killing adults.
Studies undertaken in Himachal Pradesh on monitoring and mass trapping of tomato pinworm using pheromone baited traps and light traps evaluated revealed use of yellow colour emitting conventional light source (100 w) to be the most efficacious when placed on ground during dawn. It was having advantage over pheromone traps in attracting both male and female moths (Anon 2021).

3. Curative measures

The curative measures include need based, judicious and safe use of insecticides when the pest is liable to inflict economic damage. 'Economic Threshold Level' (ETL) is an attempt to improve decision making practices by using partial economic analysis on the impact of management practices. At ETL, the benefit of pest management practices is equal to the losses caused by insect-pests.
Literature reviewed revealed that ETL has yet not been established for all the insect and mite-pests of protected environment. However, action threshold levels have been established for few insects-pests in different crops under Indian conditions. Action threshold level determined for *M. persicae* was very low (upto 0.2 aphids/ plant), suggesting managing the aphid pest with the initiation of infestation (Sharma et al. 2021). However, in cucumber, avoidable loss in marketable yield due to infestation by red spider mite was as high as 53.3 per cent. The action threshold level of 0.6 mites per leaf was established for the infestation initiated 4-weeks after transplanting (WAT). Whereas, for the infestation initiated 6 and 8-WAT, the EIL of 0.9 and 2.3 mites per leaf was established (Ghongade and Sood 2021).
Control of insects with chemicals is known as chemical control. Insecticides are the most powerful tools available for use in pest management. They are highly effective, rapid in curative action, adoptable to most situations, flexible in meeting changing agronomic and ecological conditions and economical (Rathee et al., 2018).

a. Whiteflies : Whitefly control is difficult and complex, as whiteflies rapidly develop resistance to chemical pesticides, therefore integration of different management practices should be done to avoid insecticide resistance. Kumar and Singh (2014) evaluated six insecticides viz., spiromesifen, cyantraniliprole, diafenthiuron, chlorfenapyr, buprofezin, oxy-demeton methyl and two botanicals viz., neem-based insecticide (Neem Baan) and Melia drupes extract for their toxicity against first instar nymphs of greenhouse whitefly. Spiromesifen was found to be the most effective followed by cyantraniliprole. Neem formulation was more toxic than *darek* drupe extract. Kashyap et al. (2016) investigated the efficacy of insecticides and bio-insecticides against the greenhouse whitefly on tomatoes. Abamectin resulted in highest mean percent reduction in immatures of *T. vaporariorum* followed by acetamiprid and buprofezin.
Singh (2017) developed an integrated greenhouse whitefly management model (Figure 13.2) comprising naturally ventilated polyhouse structure fitted with double door and insect-proof net of 27 × 32 mesh; installing self made yellow sticky traps made up of thick yellow paper sheet smeared with mustard oil 15 days prior to transplanting @ 1 trap per 10 m^2 ; using 25% higher dose of potassium fertilizer to the recommended dose of fertilizer (RDF) and soil application of imidacloprid (1day after

transplanting) alongwith action threshold based (5 adults per leaf) foliar applications of spiromesifen and thiamethoxam. It resulted in lower incidence of *T. vaporariorum* and high incremental output – input ratio.

Efficacy of natural products, biopesticides and insecticides against greenhouse whitefly on cucumber under protected environment evaluated as preventive and curative measures revealed the *Tamarlassi* (10.0 %) tobe most efficacious (Shalika 2021). It was followed by fermented cow urine (5.0 %) and fermented buttermilk (10.0 %). Amongst chemical insecticides, soil application of imidacloprid (0.009 %) was the most efficacious as preventive measures. However, in curative measures, alternate application of spiromesifen (0.02 %) and thiamethoxam (0.008 %) proved most efficacious.

b. Aphids: Foliar application of acetamiprid 20 SP (1 g/L water)/lambda-cyhalothrin 5 EC (1 ml/ l) on the appearance of the aphid on the crop is suggested. Use of Insect Growth Regulators (IGR): IGR (biorational insecticide formulations) such as Neemazad, Preclude, Enstar II, Azatin etc. are active against aphids and other sucking insects. IGRs typically kill insects by disrupting their development (Zhao et al. 2017; NPIC, 2020).

c. Mites: Application of propargite 57 EC/(10 ml), spiromesifen 22.9 SC/(5ml), hexythiazox 5.45 EC (10 ml) or sulphur 80 WP (30 g) or propargite 57 EC (l0 ml) in ten liter of water with the appearance of mite damage symptoms on infested and adjoining plants as spot treatment was found to be efficacious for the management of red spider mite and yellow mite. Results of study conducted by Bhullar et al. (2021) revealed that the homemade neem fruit aqueous extract (50 g/L) was moderately effective causing 41–62% reduction in the mite (both *P. latus* and *T. urticae*) population in capsicum under protected cultivation.

Indigenously prepared natural products like *Darekastra* and vermiwash also proved promising in reducing *T. urticae* population in parthenocarpic cucumber grown under protected environment (Thakur and Sood 2019, Thakur and Sood 2022). Both the products resulted in lower mite population when applied as preventive sprays 85 days after transplanting of the crop. *Darekastra* also proved an effective bioacaricide in reducing mite population when applied as curative spray. Both the products also enhanced fruit yield of the crop.

d. Thrips: Six novel insecticides viz. Boom-Tet 2% suspension (T_1), Redux 12% suspension (T_2), Azadirachtin 5% EC (T_3), Fipronil 5% SC (T_4), Abamectin (T_5), and Diafenthiuron (T_6) were evaluated by Maity et al. (2015) against chilli thrips, *Scirtothrips dorsalis*. It was revealed that among different treatments, T_4 proved the most promising in keeping the thrips population much lower as compared to control, producing the highest yield followed by T_5, T_6 and T_1. Sunitha and Narasamma (2018) reported that for the management of thrips Solar light traps + insecticide molecules (Spinosad 45SC @ 0.1ml/l and emamectin benzoate 5SG @ 0.25g/l) were significantly superior over the treatments with insecticides alone.

e. Caterpillars and leaf miners: The experiment conducted by Bhati (2020) revealed that maximum (82.50%) mortality of *Spodoptera litura* was observed at inoculum level 20,000 IJs/plant of *S. carpocapsae* after 9th day of inoculation. IIHR scientists developed the effective package for the control of Tuta consists of use of incandescent bulb @ one bulb/150 m^2 + 1 pheromone trap/300 m^2 and need based spray of spinosad 0.25 ml/l or flubendiamide @ 0.20 ml/l at 3 weeks of interval, coinciding with the peak emergence of the Tuta adults, spray of deltamethrin 2.5 EC @ 1 ml/l for killing adults of Tuta is suggested. Spray of abamectin (50ml/acre) and chlorantraniliprole (50ml/acre) is suggested for the effective control of leaf miner.

Chemical insecticides, biopesticides and natural products were evaluated for the management of tomato pinworm in Himachal Pradesh (Anon 2021). Amongst, biopesticides and natural products they found *Bacillus thuringiensis* @ 5 ml/l as most efficacious in reducing blotched leaves by 67 per cent. It was followed by azadiractin 0.15% (@ 3ml/l) (52%), *Beauveria bassiana* @ 5 g/l (40%) and *Brahmastra* @ 10 ml/l (39%). However, chemicals like flubendamide 39.35 SC (0.3 ml/l) proved to be most efficacious resulting in 82% reduction in blotched leaves followed by emamectin benzoate

5WG (0.4 g/l) (79%).

The increasing need for higher crop production under protected structures brings with it problems linked to large monocultures and pest attacks. Chemical pest control has to be reduced owing to its unwanted effects on non-targeted organisms and pest resistance. Thus, alternative and sustainable long-lasting pest control methods are urgently needed to enhance the activity of beneficial organisms. Role of public-private partnership in production, distribution and quality control of different components of IPM such as resistant varieties, natural plant products, bio-pesticides and natural enemies is imperative, otherwise there will be continuous talk on alternative methods of control for next many years.

Implementing IPM practices can enhance the environmental benefits, and improve the health of high value crops and the farm systems. Insect-pests under protected cultivation can be effectively managed by incorporating the subsequent practices such as growing insect free transplants, planting early, controlling weeds, operating insect traps, regular monitoring, timing and applying insecticides on ETL basis and immediate destruction of crop on completion of harvest to ensure success in pest management. The need for more healthy foods is stimulating the development of techniques to increase plant resistance to phytophagous insects.

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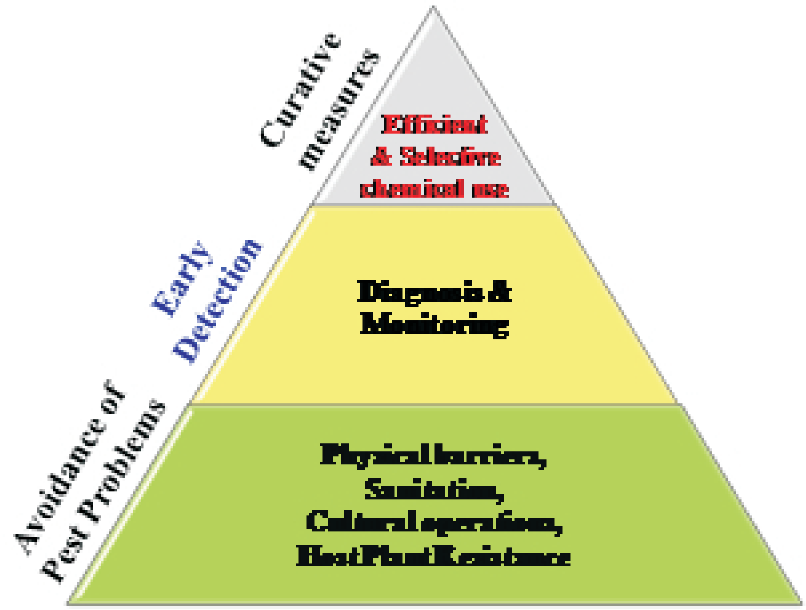

Figure 13.1 Paradigm for IPM under protected cultivation (Sood 2012)

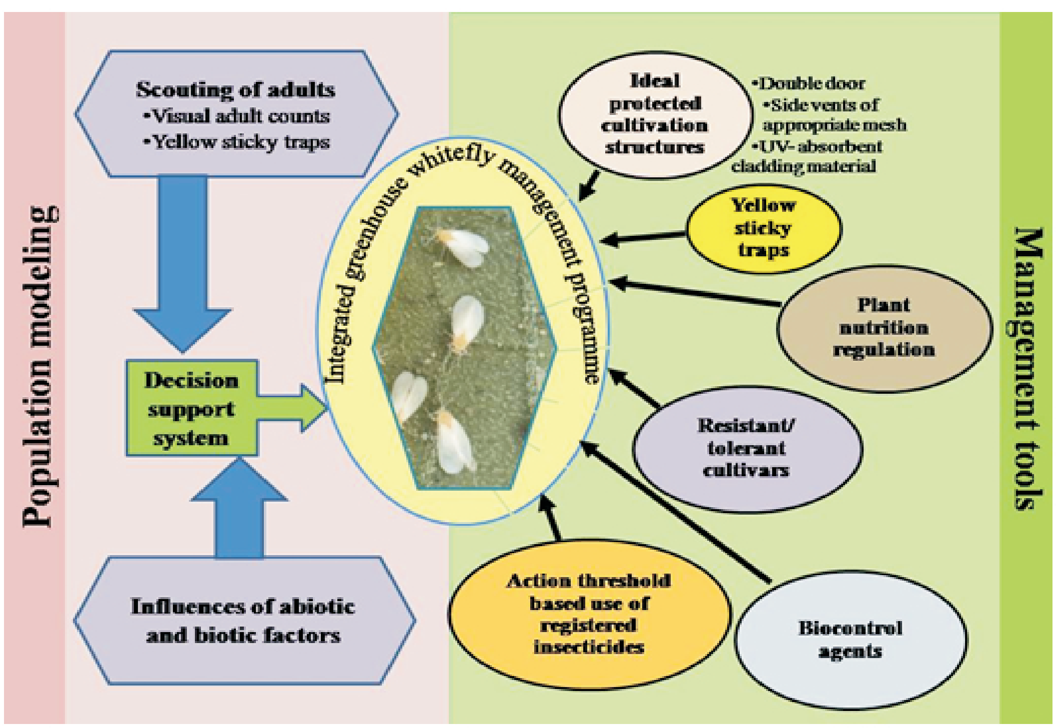

Figure 13.3 Holistic model evaluated for greenhouse whitefly management in tomato under protected cultivation

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14.ECO-FRIENDLY APPROACHES FOR THE MANAGEMENT OF INSECT PESTS IN VEGETABLE CROPS

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Abstract: Insect pests are major biotic stresses in vegetable production, which may lead to a total yield loss due to direct (feeding on plants) and indirect (vectors of viral disease) damages. Farmers use the pesticides indiscriminately that increase the pesticide load on vegetable crops resulting into environmental pollution and health hazards. Excessive residual pesticidal residues necessitates a planned integrated pest management (IPM) approach against insect pests which will lead to higher yields and increased profits. IPM approaches involve every component of management practices that keep pest population below economic injury levels, so as to reduce residual toxicity and economic loss to the growers. In the present chapter, weak phases in the life cycle of insects, nature of damage and eco-friendly non-chemical management strategies of important insect pests of vegetable crops are discussed.

Introduction

Vegetables are an important part of our daily diet as a source of vital nutrients required for normal functioning of human metabolic processes and for maintenance of our body. They contain vitamins, minerals, protein and fiber in sufficient amounts that can help to keep us healthy. Globally, India ranks second in vegetable production with a contribution of 15.4 per cent (Halder *et al.,* 2018) and is a large producer and consumer of vegetables. Vegetable crops are highly vulnerable to insect pests and diseases attack mainly due to their tenderness and softness as compared to other crops. In general, among various factors for low production and productivity of vegetables, insect pests cause heavy qualitative and quantitative losses from sowing to maturity.

Now a days, the demand for pesticide residue free vegetables has increased due to enhanced awareness among health-conscious consumers. The insect pest problem in vegetables is increasing because of monoculture, overlapping of crops, excess use of fertilizers and pesticides, and continuous availability of preferred host plants etc. Year-round cultivation and indiscriminate use of pesticides has led to many problems like resistance, resurgence, outbreak of secondary pests, contamination of food and water, destruction or elimination of natural enemies and deleterious effect on non-target organisms (Sarwar, 2014). Tomato, cucmber, capsicum, brinjal, potato, cabbage, cauliflower, chilli, okra, onion, peas, many cucurbits etc. are the major vegetables grown under North Western Plain Zone and Hill Zone of the country and these are attacked by number of insect pests. Sucking insect pests like aphids, jassid, whitefly and thrips, lepidopteran pests and fruit flies cause huge losses. Various suitable techniques are being followed for the production of quality vegetables all over the world to meet the demand of good quality vegetables throughout the year. Vegetable growers mainly rely upon chemical pesticides to counter the prevailing insect pests. The sole reliance on the insecticidal sprays is not enough to tackle the pest problems and warrants use of alternative non-chemical approaches, described as any method employed to reduce the pest populations by manipulation of the ecosystem. Thus, there is an urgent need to develop and follow the integrated pest management practices which can lead to higher yields and increased profits. In this context, knowledge, identification, and damage symptoms of particular pest, and application of management approaches are of vital importance. Weak phases in insects' life cycle, nature of damage and eco-friendly management strategies of important insect pests of vegetable crops are discussed below:

1. Tomato (*Solanum esculentun* Milliere)

Tomato is an important vegetable crop and ranks second in the world after potato, whereas it ranks third in priority after potato and onion. India is the third largest producer of tomato after China and USA. Biotic stresses cause 30-35 per cent loss in crop yield (Sardana and Sabir, 2007). The major insect pests of tomato crop are discussed here under:

Fruit borer, *Helicoverpa armigera* Hubner (Lepidoptera: Noctuidae)

Tomato fruit borer causes major damage to the crop. It is a polyphagous and destructive pest that infests more than 180 plant species belonging to 45 families in India (Manjunath *et al.*, 1989). Females lay majority of eggs on upper and lower surfaces of leaves. Young larvae scrap the foliage whereas, older larvae bore circular holes in older fruits. They thrust the head inside the fruit and eat inner content and the rest of the body hangs outside.

Management strategies:

- Avoid planting tomato near alternate hosts to prevent heavy infestations.
- Set up pheromone trap with Helilure @ 10-12/ha and change the lure after 15 days.
- Deep ploughing after summer showers exposes pupae to sunlight which get killed hence, greatly reduce the pest abundance and prevent the pest population buildup.
- Collect and destroy grown up larvae and infested fruits.
- Place 15-20 bird perches in one ha for inviting insectivorous birds for its eco-friendly management.
- Planting of yellow tall marigold or *Bidil rustica* tobacco around tomato field has been found promising. The eggs of *H. armigera* deposited on flower buds could be destroyed by the inundation of *Helicoverpa* adapted strain of egg parasitoid *Trichogramma chilonis*. Encourage the activity of parasitoids *Eucelatoria bryani*, *Campoletes, Chelonus* etc. Use of nuclear polyhedrosis virus (NPV) and *Bacillus thuringiensis* @ 500 g/ha at 10 days interval are effective against fruit borer (Rai *et al.,* 2014). *Heterorhabditis bacteriophora* can be used as an effective entomopathogenic nematode causing 74 per cent mortality in *Helicoverpa* spp. (Vashisth *et al.,* 2019). *Metarhizium anisopliae*, *Beauveria bassiana* and *Nomuraea rileyi,* being the most virulent pathogens, can be promising agents against fruit borer (Nahar *et al.,* 2004).
- *Serratiam arcescens* strain SRM can be suitably exploited for the management of *H. armigera.*
- Natural enemies such as *Trichogramma chilonis* and *Chrysoperla carnea* can be released starting from flower initiation stage and inundative release of *T. brassiliensis* at 50,000 eggs/ha alone beginning with fruiting is useful (Rai *et al.,* 2014).
- Spray neem-based formulations to kill early instar larvae.
- Integration of pheromone traps, neem seed kernel extract, *T. chilonis* and *Braconhebetor* are quite effective (Rahman *et al.,* 2016).

Whitefly, *Bemisia tabaci (*Gennadius) (Hemiptera: Aleyrodidae)

It is a serious pest of field and horticultural crops throughout the world (Bayhan *et al.,* 2006), globally distributed and occurs in all continents except Antarctica (Martin *et al.,* 2000), and is known to infest more than 600 plant species (Stansly and Naranjo, 2010). It is quite serious on brinjal, cucurbits, chilli, capsicum, okra, beans, tomato and potato.

The buildup of whitefly is due to many factors as listed below:

1. Round the year cultivation of preferred hosts, weeds and volunteer plants in and around the fields during off season and high reproductive rates provide optimal conditions for the development of whitefly population.
2. The non-judicious use of fertilizers and irrigation water along with susceptible cultivars further boost the pest.
3. The mild winter conditions in plains of North India elicit carryover of whitefly.
4. The indiscriminate and non-judicious use of insecticides, particularly synthetic pyrethroids, induces insecticide resistance and resurgence of whitefly and may also affect the natural enemy complex, including general predators.

It is polyphagous in nature and prevalent throughout India. Its main hosts include cotton, tobacco and vegetables viz., tomato, brinjal etc. Whitefly, is a vector of leaf curl and yellow mosaic virus. On hatching, nymphs crawl for some distance and settle down on a succulent spot on ventral surface of leaf, and continue to suck sap. Affected parts become yellowish, leaves wrinkle, curl downwards and ultimately shed. Honeydew excreted by nymphs attracts sooty mold which forms black coating on the leaves.

Management strategies:

- Grow tolerant variety like PB Varkha Bahar-1 and PB Varkha Bahar-2
- Adults should be sampled early in the morning, as the crop boundries of the field is usually first to be infested if the adults are moving into the crop from other infested areas.
- To avoid unwanted use of insecticides, economic threshold levels should be adopted.
- The use of sound cultural practices viz., crop rotations, host free period is useful as it will prevent the continuous availability of host plants for whiteflies and ultimately reduce their build up.
- Insect free seedlings should be used as young plants are generally more vulnerable to damage and early infestations should be checked.
- Removal of weed flora in and around vegetable fields during the crop season helps in checking the build-up of whitefly population in subsequent crops.
- Use adequate and judicious nitrogenous fertilizers, as excessive nitrogen increases the population of whitefly.
- Whitefly adults are attracted to the yellow color, so place yellow sticky cards/yellow plates/tins coated with grease in the field so that the attracted whiteflies get stuck to the sticky material. Moreover, lower levels of infestation may be monitored by yellow sticky traps.
- Conservation and augmentation of biological control agents may be encouraged by avoiding or delaying the use of broad spectrum insecticides. Use predators (ladybugs, lacewings) or parasitoids or *Verticillium lecanii.*
- Plant oils including neem oil and neem seed kernel extract are effective in the initial stages of crop, especially the early season treatments should be limited to neem based formulations and insect growth regulators.
- Integrated management of whitefly is the cost, eco and farmer friendly option.

Serpentine leaf miner, *Liriomyza trifolii* (Diptera: Agromyzidae)

It is the most common leaf miner pest of tomato since 1990. Leaf miners generally attack late summer tomatoes. Leaf miner feeding leads to serpentine mines (slender, white, winding trails) and heavily mined leaflets have large whitish blotches. Leaves injured by leaf miners drop prematurely and heavily infested plants may lose most of their leaves. It occurs early in the fruiting period. Defoliation can reduce yield and fruit size and exposes fruit to sunburn. Pole tomatoes with long fruiting period are more vulnerable.

Management strategies:

- Check seedlings before planting and destroy the infested ones.
- Parasitic wasps, viz., *Chrysocharis parksi* and *Diglyphus begini* attack leaf miner.
- In areas, where tomato crop is planted continuously, early infestations in new crop may be reduced by removing old crop immediately after the last harvest.
- Apply neem cake in furrows @ 250 kg/ha at the time of planting and repeat it after 25 days and spray neem seed powder extract @ 4% or neem soap @ 1%.

Tomato pinworm, *Tuta absoluta* (Lepidoptera: Gelechiidae)

It is an invasive pest to India. Tomato is the main host plant, but it can also attack other crop plants including potato, eggplant, pepper and tobacco. Larvae make tunnels on leaves and feed inside the tunnel by scraping the chlorophyll, later older instars make pin hole on the upper surface of the tomato fruit.

Management strategies:

- Use of sex pheromone for *T. absoluta* and yellow delta sticky traps.
- *Nabis pseudoferus,* a species of damsel bug is a promising biological control agent. Application of Bt formulation is effective.

2. Brinjal

Brinjal shoot and fruit borer, *Leucinodes orbonalis* Gunnee (Lepidoptera: Pyraustidae)

It is the most destructive pest of brinjal, found throughout the country causing as high as 70 per cent infestation. The pest remains active throughout the year, except in severe cold weather in North India. Infestation starts after few weeks after transplantation. The larva bore into the growing shoots or petioles of large leaves and feed on internal tissues. The affected shoots wither and the plants exhibit the symptoms of drooping. After fruit formation larva leads their entry under young calyx. The holes become plugged with excreta leaving no visible sign of infestation. The large exit holes become visible on fruits. The pest survive in the previous season debris or in the stalks of brinjal plants, as most farmers leave the debris plants around their fields and use as fuel.

Management strategies:

- Cultivation of shoot and fruit borer tolerant varieties such as Punjab Barsati, Punjab Neelam and BH-2 (Anonymous, 2018). Varieties with long and narrow fruits are less susceptible, therefore, these varieties should be preferred.
- Continuous cropping of brinjal and ratooning should be avoided. All the infested shoots and fruits should be destroyed at regular intervals till harvest.
- Installation of pheromone traps @ 1/ha for monitoring and @ 100/ha for mass trapping or use light traps to attract and kill insects. Cover the seedlingswith 30-mesh nylon net to prevent the entry of adult moths (Srinivasan, 2009)**.**
- Intercropping with cluster beans reduces shoot and fruit damage (Elanchezhyan *et al.*, 2008). Intercropping of brinjal with two rows of coriander was effective to reduce damage (David, 2000).
- Avoid using synthetic pyrethroids as these lead to resurgence of sucking pests.
- Natural enemies *Pristomerus testaceus* Mori and *Cremastus flavorbitalis* Cam. (Ichneumonidae), *Eriborus argentiopilosus Bracon* spp., *Shirakia shoenobii* Vier and *Iphiaulax* sp. (Braconidae), *Apanteles* spp., *Chelonus* spp., and the chalcids *Brachymeria obscurata* (Walker) are highly effective. Weekly release of egg parasitoid, *Trichogramma chilonis @ 1g* parasitized eggs/ha/week and larval parasitoid, *Bracon habetor @ 800-1000 adults/ha/week*were found effective (Alam *et al*., 2006).
- Application of neem cake four times during the crop growth decreases the incidence of borer to eight per cent as against 40 per cent in control.
- An IPM module comprising neem (1%) @ 600 ml/acre, *Metarhizium anisopliae* @ 2 kg/acre alongwith clipping of infested shoots, destruction of infested fruits and reduced risk chemicals was highly effective.

Leaf hopper, *Amrasca biguttula biguttula* (Cicadellidae: Hemiptera)

This pest is distributed all over India but it is more serious in Punjab and Tamil Nadu. It is a polyphagous pest and attacks okra, brinjal, beans, castor, cucurbits, hollyhock, potato, sunflower and other malvaceous plants. The nymphs and adults are restricted to under surface of the leaves and suck the cell sap and inject their toxic saliva. The plants become stunted with crinkled leaves which become yellowish and cup shaped with brownish or reddish coloured edges of the leaves. The first and second instar nymphs feed mostly near the base of the leaf vein, and then scatter throughout the leaf and feed from the under surface.

Management strategies:

- Clean cultivation is effective tool for reducing pest population.
- Conserve the spider population in the field.
- Grow other group of crops in next season.
- Avoid using synthetic pyrethroids to avoid resurgence of sucking pests.
- Judicious use of nitrogenous fertilizers, as higher doses make the plant prone to jassid attack.

Hadda beetles, *Epilachna* spp. (Coleoptera: Coccinellidae)

This pest commonly occurs throughout South-East Asia and cause severe damage from May to September. It also attacks bitter gourd, bottle gourd, potato and tomato.Both grubs and adults feed by scraping chlorophyll from epidermal layers of leaves, leaving the veins and veinlets, and cause characteristic skeletonized patches on the leaves and form ladder-like windows. In severe cases, calyx of the fruit is also damaged. Later, the affected areas on leaves dry and fall off and damage appears in the form of leaf shot holes. Infested leaves turn brown dry up and fall off and completely skeletonize the plants.

Management strategies:

- Collect and destroy egg masses and skeletonized leaves with grubs, pupae and adults.
- In small holdings and kitchen gardening hand picking of grubs and collection of beetles by hand nets in the early stages of attack is effective.
- Remove alternate hosts and weed plants.
- Natural enemies *Tetrasatichus ovulorum*, *Chrysonotomia appannai* and *Pediobius foveolatus* may be effectively used.

***Whitefly, Bemisia tabaci (Gennadius) (*Hemiptera: Aleyrodidae)**

It is prevalent in most of the countries and attack several crops including vegetables. Females lay eggs singly on the underside of the leaves which are stalked, sub-elliptical and light yellow which turn brown later on. The nymphs are elliptical and soon after hatching insert their mouthparts into the plant tissues. The affected parts become yellowish, leaves wrinkle and curl downwards and are ultimately shed. The insects also exude honeydew which favours the development of sooty mold. The attacked crop gives a sickly and black appearance, and plant growth is adversely affected. The attack in the late season results in significant reduction in the yield.

Management strategies:

- The decision on spray of insecticides should be based on economic threshold level (ETL). Whitefly population may be monitored from three leaves i.e., one each from top, middle and bottom canopy from 10 randomly selected plants from the middle in each of the four quarters of one acre in the morning before 10 AM. When the mean whitefly population reaches economic threshold level of nine adult/leaf, spray the crop with recommended insecticides.
- Regular monitoring of the crop and Regular surveillance on alternate host crops should be done to check infestation and timely management of whitefly.
- Weeds should be eradicated from field bunds, waste lands, road side and irrigation channels/canals to avoid its further spread to brinjal fields.

- The flies are attracted to yellow colour, hence place yellow plates/tins with grease to attract flies which get stuck to the grease. Yellow sticky traps are also helpful to monitor and suppress infestations.
- Release natural predators such as ladybugs, lacewings, or whitefly parasites.
- Do not spray synthetic pyrethroids like deltamethrin, cypermethrin and fenvalerate as these leads to resurgence.
- In the beginning of crop season, 1-2 sprays of PAU Neem Extract @ 1200 ml per acre or maize/sorghum/bajra juice @ 1500 ml/acre should be given in 100-125 litres of water.PAU Neem Extract can be prepared by boiling 4.0 kg terminal shoots of neem trees including leaves, green branches and fruits in 10 liters of water for 30 minutes. Then filter this material through muslin cloth and use the filtrate for spraying at the recommended dose.
- Nursery beds should be covered with nylon net or sprayed with neem formulation.
- Continuous cropping of brinjal should be avoided.

3. Cole Crops

Cabbage **(***Brassica oleracea* var *capitata*) and cauliflower (*Brassica olercea* var *botrytis*) are grown in cold and moist climate. Cole crops are attacked by number of insect pests which cause heavy economic losses and major insect pests are described here:

Diamondback moth, *Plutella xylostella* Linn. (Lepidoptera: Plutellidae)

Diamondback moth is a serious pest during the months of February-March and August-September and causes substantial yield loss in the plains. Caterpillars damage the plant by feeding on leaves of cauliflower, cabbage and rapeseed. The neonates feed in mines on lower side of the leaves and, in the later instars they feed on exposed leaves and form parchment like membrane by making shot holes. The growth of young plants is greatly retarded. Central leaves of cabbage or cauliflower may be riddled and the vegetable is rendered unfit for human consumption.

Cabbage caterpillar, *Pieris brassicae* (Linnaeus) (Pieridae: Lepidoptera)

In India, it is widely distributed along the entire Himalayan region and is comparatively more common and destructive. It causes severe damage to cabbage, cauliflower, radish and turnip. The pest passes winter in the plains and migrates to hilly regions during the summer. During September to April, it breeds on rape and mustard. On hatching, the young caterpillars feed gregariously on leaves for a couple of days and disperse thereafter, spreading infestation to the adjacent plants and fields. Feeding leads to skeletonized leaves, and sometimes the caterpillars bore into the heads of cabbage and cauliflower.

Tobacco caterpillar, *Spodoptera litura* (Fabricius) (Lepidoptera: Noctuidae)

It is polyphagous in nature and becomes serious during August-October and February-March. Initially the larva feed on leaves and fresh growth of the plant gregariously for a few days and then disperse and feeds solitary.

Cabbage borer, *Hellula undalis* (Fabricius) (Lepidoptera: Pyralidae)

This pest is distributed all over the country. The larvae bore into the central shoots and the plant is unable to bear the flower head. The attack is mostly on young plants in the nursery and the fields. The caterpillar first mine into the leaves and then feed on the leaf surface, sheltered within the silken passages. The larva increases in size, bore into the heads of cauliflower and cabbage and prevent head initiation leading to multiple shoot or head formation.

Management strategies:

- Eliminate weeds and previous crop residue.
- Remove and destroy egg masses and clusters of larvae.
- *Release of Apanteles plutellae @* 1000 adults every two-week interval till harvesting, helps to

check DBM population. Pentatomid predator, *Eocanthecona furcellata* feed voraciously on cabbage butterfly.

- Integration of various management practices i.e., releases of *Chrysoperla* @ 5 larvae/plant and 5% neemazal + mechanical collection of insect+ planting of mustard crop on the boarder + release of *T. pieridis* @1,00,000/ha + spray of Delfin WG @ 300 g/acre has been found effective for the control of cabbage caterpillar (Kaur and Virk, 2015).
- Microbials derived from actinomycetes, bacteria and fungi and the viruses were very effective against these pests. Give 3-4 sprays of NSKE 5% at 10-15 days interval.
- Use Bt formulation Dipel 8L, Halt WP or Delfin 8L @ 750ml/ha for DBM.

Cabbage aphid, *Brevicoryne brassicae* (Hemiptera: Aphididae)

Cabbage aphid was originally confined to Palaearctic or Holarctic regions but at now it is widely distributed. Colonies of the insects are often found on tender shoots and leaves. Sucking of vital sap from the tissues result in stunting of plants leading to poor head formation. Severe infestation may lead to complete drying of the plants. Infested seedlings on losing their vigor, get distorted and become unfit for transplanting. The aphids produce honeydew making the plants sticky.It favors the growth of sooty mould resulting into formation of black coating on affected plant parts hindering the photosynthesis and adversely affecting the plant growth.

Management strategies:

Yellow sticky traps alongwith neem spray can be effectively used for managing aphids.

4. Chilli And Capsicum

Thrips, *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae)

Scirtothrips dorsalis attacks more than 100 host plants belonging to 40 different families. The nymphs resemble the adults in shape and colour but are wingless and smaller in size. Nymphs and adults cause damage by sucking cell sap from tender regions and cause shriveling of leaves. The attacked plants remain stunted and dry up. Severe infestation causes malformation of leaves, buds and fruits.

Management strategies:

- Change in date of sowing and transplanting reduce the attack of sucking pests. Under South Indian rain fed conditions sowing and transplantation of nursery on 15th June and 15th July, respectively, recorded significantly low sucking pest population.
- Chilli crop bordered by two rows of maize at every 0.5 acre area and its spray with Neemazal 1% @ 2 ml per liter at 7 weeks after transplanting (Tatagar *et al*., 2011) reduced the insect pest population.

5. Okra

Cotton jassid, *Amrasca biguttula* Ishida (Hemiptera: Cicadellidae)

It causes damage during May to September and also infest potato, brinjal, tomato, etc. Damage to the crop is caused by adults and nymphs, which are very agile and move briskly, forward and sideways. They suck cell-sap from the abaxial leaf surface and feed constantly on the plant juice. Plants are injured due to the loss of sap and injection of toxins. The infested leaves turn pale and rust red in colour, hang downwards, dry up and fall to the ground.

Management strategies:

- Use tolerant varieties viz., Punjab-7, Punjab-8, Parbhani Kranti, Varsha Uphar, Arka Anamika, IC-7194 etc.
- Sowing of crop after June 15 harbours lesser jassid population.
- Monitor population of nymphs after germination in three leaves i.e. one each from top, middle and bottom canopy from 10 randomly selected plants in the middle of the four quarters of one

acre. If jassid population exceeds economic threshold level (4 nymphs/leaf), spray the crop with 80 ml Ecotin 5% (neem based insecticide) or 2000 ml PAU Neem Extract.

- Parasitoids *Erythmelus empoascae, Stethymium empoascae*, *Chrysoperla* and spiders are active against this pest and needs to be conserved.
- NSKE and neem oil are also effective to control jassids (Sakthivel *et. al.,* 2007).

Spotted bollworm, *Earias insulana and E. vittella* (Fabricius) (Lepidoptera: Arctidae)
This pest is polyphagous and cause damage during May to September. Eggs are usually laid singly on buds and flowers and occasionally on fruits. During early growth stage, the eggs are laid on shoot tips. In few weeks old young crop, the freshly hatched larvae bore into tender shoots and tunnel downwards and such infested shoots wither, droop down and ultimately the growing points are killed. The side shoots may proliferate giving the plants a bushy appearance. The caterpillars bore inside the newly formed buds, flowers and fruits and feed on the inner tissues. The damaged buds and flowers wither and fall without bearing any fruit whereas, the affected fruits become misshaped and remain stunted.

Management strategies:

- Cultivation of resistant varieties viz., Punjab-8, Clemson Spineless, MP-7, AE-57 etc.
- Avoid cultivation of okra in and around the cotton fields and infested fruits should be regularly removed and buried in deep soil. Cultivars with large number of longer and broader, trichomes are less preferred for oviposition.
- Marigold as intercrop and maize as border crop reduce the pest incidence.
- Pheromone traps @ 25 traps/ha in okra are effective for shoot and fruit borer.
- Uproot the host plants of hollyhock and ratooned cotton and deep plough the field to expose resting pupae. Avoid monocropping of okra year after year and remove debris and all the alternate host plants from field.
- Predators, *Chrysoperla carnea* and *Chelonus blackburni* released @ 25 000 larvae/ha and @ 75 000 adults/ha, respectively (Praveen and Dhandapani, 2001; Dhane, 2007), were effective.
- Commercial formulations of *Bt kurstaki viz.* Biolep and Bioasp were also effective.
- ETL for *E. vittella* on okra is 1per cent fruit infestation and spray the crop with neem seed kernal extract @ 5 ml/l after flowering.

6. Cucurbits

Fruit fly, *Bactrocera cucurbitae (Coquillett)*(Diptera: Tephritidae)
Fruit flies are highly damaging for cucurbitaceous crops and the preferred hosts are squash, melon, cucumber etc. The infestation varies from 30-100 per cent in different cucurbitaceous crops. Other hosts include solanaceous plants (tomato, eggplant, pepper, etc.). Fruit flies cause 30-40% damage in vegetable and fruit crops with economic losses amounting to Rs. 7000 crore annually in India. The female fly makes a puncture in the soft fruits with the help of its sharp ovipositor and inserts the white, cigar-shaped, slightly curved eggs singly or in groups into the flowers and tender fruits. The freshly hatched maggots bore into the fruit pulp by forming serpentine galleries, contaminate these with its frass and provide entry points for saprophytic fungi and bacteria, leading to rotting of the fruit. Feeding on pulp results in premature dropping of fruits and make them unfit for consumption. The fully grown maggots come out of the fruits, drop to the ground and pupate in the soil.

Management strategies:

- Fruit fly population is low in hot dry months and is at peak during rainy season.
- Apply the bait spray (200 g gur/sugar+20 ml malathion/ cypermethrin +20 litres of water). Moreover, flies have the habit of resting on tall plants like maize. Hence, grow maize in rows at a distance of 8-10 m in cucurbits and the bait can be sprayed on maize.

- Collect the infested fruits and destroy them by burying deep in soil.
- Fruit infestation can be higly reduced by enclosing fruits in paper bags.
- It can be managed by installing fruit fly traps @ 16 traps/acre and spray of Nimbex (0.15%).
- Male annihilation and sterile insect release have been used to eradicate some populations of *B. cucurbitae.* SIT was used to eradicate *B. cucurbitae* from Kume Island, Japan (Shiga, 1989).

Red pumpkin beetle, *Raphidopalpa foveicollis* Lucas (Coleoptera: Chrysomelidae)
It is a serious pest of cucurbits especially at the seedling stage. Adult beetles feed voraciously on the leaf lamina by making irregular holes and the maximum damage is done at the cotyledon stage. The first generation is more injurious than the subsequent generations. The adult insect also feeds on the leaves of grown up plants by scrapping off their chlorophyll and leaves show net like appearance. The attacked plants may wither away warranting the re-sowing of the crop. The grubs cause damage by boring into the roots, underground stem portion and by feeding on the leaves and fruits line in contact with the soil. The damaged roots, underground and stem portions may rot due to infection of saprophytic fungi.

Management strategies:
- Net barrier can be used for the protection.
- Collection of beetles using hand nets in the morning when these are sluggish and their killing in kerosenised oil.
- Dust dung ash on the plants 3-4 times at weekly interval after their germination.
- Spray of neem based formulations like Econeem and Nimbecidine and deltamethrin/ malathion are effective.
- The soil around the plant roots should be sprayed with strong insecticides to kill developing grubs and the fields should be ploughed to expose and kill grubs in soil after the crop harvesting.

7. Peas, *Pisum sativum* (Linn.)

Leaf miner, *Chromatomyia horticola* (Goweau) (Diptera: Agromyzidae)
It attacks many vegetable and flower hosts, including cole crops, cucurbits, tomatoes, peas, beans, aster, begonia, dahlia, impatiens, lily, marigold, petunia, and verbena. Leaf miner feeding results in serpentine mines (slender, white, winding trails) and heavily mined leaflets develop large whitish blotches. Leaves injured by leaf miners drop prematurely and heavily infested plants lose most of the leaves. Its occurrence during early fruiting period leads to defoliation and reduction in yield.
Management strategies:
- Check the plant for signs of leaf miner damage and use yellow sticky traps/cards for leaf miner adult flies.
- Remove plants from soil immediately after harvest
- Use tomato or marigold as a trap crop for the management of leaf miner.
- Several species of parasitic wasps especially *Chrysocharis parksi* and *Diglyphus begini* attack leaf miner larvae.
- Neem oil 0.03% @ 5ml/litre of water is very effective under mid hill conditions of Himachal Pradesh (Sharma *et al.,* 2014)

Pea pod borer, *Etiella zinckenella* Treitschke (Lepidoptera: Pyralidae)
Etiella zinckenella is a cosmopolitan pest of worldwide distribution and attacks cultivated legumes including cowpea, garden pea, lima bean, mung bean, pigeon pea, common bean (*Phaseolus vulgaris*) and soyabean. The larvae after emergence, feed on the young leaves, blossom, buds and pods. It bores into the pod and eat away a part of the newly formed seed and move to the next. Silk and fecal material accumulates in the pods. In heavy infestation small pods fall prematurely and the old pod remain

attached to the plant.

Management strategies

- Deep autumn plowing up to a depth of at least 20 cm is recommended.
- Early season planting helps to escape infestation because the crop reach maturity before pod borers attains high densities.

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15 ECOLOGICAL ENGINEERING STRATEGIES FOR MANAGEMENT OF PESTS IN AGRO-ECOSYSTEMS

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Abstract: The pressure exerted by human activities, that are much against the defined ecosystem services, the resultant state in terms of community composition and ecosystem processes, and the increasingly important management responses to overcome these negative impacts of anthropological have led to paradigm shift in the strategies for insect pests and disease management in agro-ecosystems. Problems generated by agricultural intensification have led to a serious decline in the farmland biodiversity. Further, oversimplification of the agro-ecosystem due to monoculture has enhanced the pest problems through increased herbivory and immigration of pests; especially, the exotic and indigenous invasive pests, due to depletion of the beneficial arthropod and vertebrate fauna, including natural enemies of pestiferous insects, insect pollinators and the productive insects. Therefore, the interest to shift pest management strategies from the intensive use of agrochemicals to sustainable and eco-friendly practices has increased – EPM through organic farming.

Introduction

Farming practices and landscape features that favour biodiversity include:maintenance of suitable hedgerows, preferring polycultures over monoculture, practicing agroforestry within the farmland, growing herbaceous strips within crops, maintaining appropriate field margins with flowering plants, and having small fields surrounded by hedgerows with a view to provide food and shelter to the much needed beneficial arthropod fauna that maintain favourable ecosystem services. These approaches reflect the notion that the quality, not the quantity, of diversity is important. This requires the selection of the 'right kind' of diversity. Hence, for successful ecological engineering or farm scaping'directed' approaches needs to be employed rather than relying on the 'shotgun' approach of simply increasing vegetation diversity. Directed approaches include studies to identify optimal forms of diversity and to better understand the ways in which natural enemies respond to vegetation diversity at local and landscape levels.

Agricultural intensification has led to a dramatic decline in farmland biodiversity. This biodiversity is directly linked to the maintenance of some ecosystem services such as pollination and pest control. An alternative to conventional farming systems is the implementation of diversification practices that increase diversity in- and around- the field to increase the incidence of natural enemies, to reduce pest pressure and to enhance crop production. The amount of crop diversity per unit of arable land has decreased and the croplands are showing a tendency towards concentration. Monoculture has resulted in simplification of the agro-ecosystem, which concentrated resources for specialist crop herbivores and increased the areas available for immigration of pests. The interest to shift pest management strategies from the intensive use of agrochemicals to sustainable and eco-friendly practices has increased in recent years. Thus, farmers and agriculturists have to be increasingly aware of the ecosystem services performed by agricultural biodiversity to achieve sustainable production. Farming practices and landscape features that favour biodiversity include:

- Hedgerows
- Polycultures
- Agro-forestry
- Herbaceous strips within crops
- Appropriate field margins
- Small fields surrounded by hedgerows

Organic farming practitioners have observed that the following features linked to agro-ecosystem biodiversity tend to enhance indigenous natural enemies and suppress pests in crops:

1. Organically managed or agro-ecosystem subjected to minimal inputs
2. Diversified cropping systems
3. Presence of flowering plants within or around the field (farmscaping)
4. Soils covered with mulch or vegetation in the off-season

5. Presence of perennial plants
6. Small fields surrounded by natural vegetation.

Biodiversity is undeniably a powerful tool for pest management, but it is not consistently beneficial. Vegetation diversity is no guarantee of lowered pest densities, either by invoking resource concentration or enemies' hypotheses.

In fact, habitat manipulation for enhanced pest control has been referred to as 'chocolate-box ecology' because of the picturesque nature of some of the tools used, eg. strips of flowers. In some cases, floristically diverse vegetation is added without prior testing and ranking of the candidate plants, but this crude approach is not universal and habitat manipulation researchers now more commonly screen plant species to determine optimal species or use a varierty of selection criteria to determine appropriate botanical composition. These approaches reflect the notion that the quality, not the quantity, of diversity is important.This requires the selection of the 'right kind' of diversity. It has been observed that parasitic Hymenoptera tended to visit only a limited number of food plants – a mean of 2.9 plant species per parasitoid species; therefore, providing nectar to a parasitoid of a key pest could fail unless an appropriate food plant species is identified by appropriate research. For habitat manipulation to evolve into a rigorous science and become a branch of ecological engineering, it needs to employ 'directed' approaches rather than rely on the 'shotgun' approach of simply increasing vegetation diversity that is implied as desirable. Directed approaches include experimental studies to identify optimal forms of diversity and to better understand the ways in which natural enemies respond to vegetation diversity at local and landscape levels.

Farmscaping is an ecological approach to pest management that usually involves planting hedgerows, insectary or flowering plants to attract and support populations of beneficial organisms. Farmscaping plants are planted to attract and provide resources (viz. shelter, reproductive habitat and alternative or supplemental food sources) to beneficial insects that may not otherwise be available in a monoculture crop field. The concept of farmscaping is partly based on the knowledge that natural enemies require supplemental food sources to achieve maximum fitness and thereby provide better pest control of pest species in agro-ecosystem.

Genetically engineered (GE)crops are likely to have profound effects on agriculture as they are more widely used, especially in the developed countries. The net effect may or may not be beneficial, and whether the risks of proceeding outweigh the potential benefits is actively debated, hence should not be blindly advocated and practiced. Much more has to be learnt before such GE crops could be adopted in a big way, both in the so called developed and developing world.

Strategies to enhance beneficial insects

One of the most powerful and long-lasting ways to minimize economic damage from pests is to boost populations of existing or naturally occurring beneficial organisms by supplying them with appropriate habitat and alternative food sources. The beneficial insects include the 3 P-s: pollinators, predators and parasitoids. Beneficial organisms such as predators, parasites and pest-sickening "pathogens" are found more frequently on diverse farms where fewer pesticides are used, than in monocultures or in fields routinely treated with pesticides.

The following characteristics are typical of farms that host plentiful populations of beneficial arthropods:

- Fields are small and surrounded by natural vegetation.
- Cropping systems are diverse and plant populations in or around fields include perennials and flowering plants.
- Crops are managed organically or with minimal agrichemicals.
- Soils are high in organic matter and biological activity and, covered with mulch or vegetation during the off-season.

To conserve and develop rich populations of natural enemies, avoid cropping practices that harm beneficial insects, arthropods and insectivorous birds, rather substitute methods that enhance their survival. Start by reversing practices that disrupt natural biological control, such as insecticide applications, hedge removal and comprehensive herbicide use intended to eliminate weeds in and around the fields. Even small changes in farming routines can substantially increase natural enemy populations during critical periods of the growing season. The simple use of straw mulch provides humid, sheltered hiding places for nocturnal predators like spiders and ground beetles. By decreasing the visual contrast between foliage and bare soil, straw mulch also can make it harder for flying pests like aphids and leafhoppers to "see" the crops they attack. This combination of effects can significantly reduce insect damage in mulched garden plots eg.:

- Carefully selected flowering plants or trees in field margins can be important source of nectar and pollen for beneficial insects.
- They also can modify crop microclimate, add organic matter and produce wood or forage.
- Establishing wild flower margins around crop fields enhances the abundance of beneficial insects searching for pollen and nectar. The beneficial insects then move into adjacent fields to help regulate insect pests.
- As an added benefit, many of these flowers are excellent food for bees, enhancing honey production, or they can be sold as cut flowers, improving farm income.

1. Increase the population of natural enemies

A well fertilized, weeded and watered monoculture is a dense, pure concentration of favorite for food insect pests. Many pests have adapted to these simple cropping systems over time. Natural enemies however, do not fare as well because they are adapted to natural systems. Tilling, weeding, spraying, harvesting and other typical farming activities damage habitat for the beneficial insects and arthropods. In addition to prey and host, natural enemies also need refuge sites and alternative food to complete their life cycles. For example, many adult parasitoids sustain themselves with pollen and nectar from nearby flowering weeds while searching for hosts. Predaceous ground beetles, like many other natural enemies - do not disperse far from their overwintering/ hibernating sites and access to permanent habitat near or within the field gives them a jump-start on early pest populations. Cabbage bordered with mustard results in significantly lower infestation of cabbage by flea beetles and diamondback moth. Cabbage intercropped with coriander results in enhanced activity of parasitoids, syrphid flies and coccinellids feeding on cabbage aphids (*Lipaphis erysimii* and *Brevicoryne brassicae*). It was evidenced by the fact that cabbage as a sole crop recorded 16 per cent parasitization, while cabbage intercropped with coriander had 23 per cent parasitization during *rabi* season 2015-16 and 2016-17 at Udaipur, India.

2. Provide supplementary resources

One can enhance the population of natural enemies by providing resources to attract or keep them on farm eg. erecting artificial nesting structures for the predatory wasps (*Polistes* spp.) intensifies its predation of lepidopteran pests. Lucerne and cotton plots, providing mixtures of hydrolyzate, sugar and water increased egg-laying by green lacewings six-fold and boosted populations of predatory syrphid flies, lady beetles and soft-winged flower beetles.

The survival and reproduction of beneficial insects can be increased by allowing permanent populations of alternative prey to fluctuate below damaging levels. By using plants that host alternative prey to achieve this; plant them around the fields and even as strips within the fields. In cabbage, the relative abundance of aphids helps determine the effectiveness of the general predators that consume diamondback moth larvae. Similarly, in many regions, anthocorid bugs benefit from alternative prey when their preferred prey, western flower thrips, is scarce.

3. Manage vegetation in field margins

With careful planning, the field margins may be converted into reservoirs of natural enemies and such habitats can be important overwintering sites for the predators of crop pests and sources of pollen, nectar and other resources for natural enemies. Many studies have shown that beneficial arthropods do indeed move into crops from field margins, and biological control is usually more effective in crop rows near wild vegetation than in field centers.

4. Manage plants surrounding fields to manage specific pests

One practice, called Perimeter trap cropping is one of the best practices when plants like cowpeas are grown to attract aphids away from main crop. In perimeter trap cropping, plants that are especially attractive to target pests, are planted around a cash crop, encircling it completely without gaps. Perimeter trap cropping can sharply reduce pesticide applications by attracting pests away from the cash crop and by limiting pesticide use in field borders or eliminating it entirely, the beneficial insects in the main crop can be preserved.

Alternately, flowering plants such as marigold, coriander, anise etc. can be grown in field margins to increase populations of syrphid flies and reduce aphid populations in adjacent vegetable crops. This method is the most effective for the pests of intermediate mobility.

5. Create corridors for natural enemies

One can provide natural enemies with highways of habitat by sowing diverse flowering plants into strips every 165 to 330 feet (50–100 m) across the field. The beneficial can use these corridors to circulate and disperse into field centers. European studies have confirmed that this practice increases the diversity and abundance of natural enemies. When sugar beet fields were drilled with corridors of tansy leaf (*Phacelia tanacetifolia*) every 20 to 30 rows, destruction of bean aphids by syrphid flies intensified. Similarly, strips of buckwheat and tansy leaf in Swiss cabbage fields increased populations of a small parasitic wasp that attacks the cabbage aphid.

6. Select the most appropriate plants

Beneficial insects are attracted to specific plants, so for managing a specific pest, choose flowering plants that will attract the right beneficial insect(s). The size and shape of the blossoms dictate the insects will be able to access the flowers' pollen and nectar. The most helpful blossoms are small and relatively open for most beneficials, including parasitic wasps. Plants from the aster, carrot and buckwheat families are especially useful.

In addition to size and shape, timing of blossoming is also important for natural enemies, Hence, the time of pollen and nectar production should also be determined. Many beneficial insects are active only as adults and only for discrete periods during the growing season and require pollen and nectar during those active times, particularly in the early season when prey is scarce. One of the easiest ways is to provide mixtures of plants with relatively long, and overlapping bloom times eg. flowering plant mixes should include species from the daisy or sunflower family (Compositae) and from the carrot family (Umbelliferae).

There is meagre information about the plants which are the most useful and appropriate sources of pollen, nectar, habitat and other critical needs. Though many plants encourage natural enemies, but extensive studies are required to determine the exact plants associated with the particular beneficial insects, and how and when the desirable plants may be made available to key predators and parasitoids. Because beneficial interactions are site-specific, geographic location and overall farm management are critical variables. Instead of universal recommendations, which are impossible to comprehend, investigations on the usefulness of alternative flowering plants at a particular farm may be more informative. Surfing of informational networks, i.e. Extension, NRCS and nonprofit organizations and other farmers may be the useful sources.

7. Use weeds to attract beneficial insect species

Weeds may be the best flowering plant to attract beneficial arthropods, but this practice complicates management. Although some weeds support insect pests, harbor plant diseases or compete with the cash crop whereas, others supply essential resources to many beneficial insects and contribute to the biodiversity of agro-ecosystems.

In the last 20 years, researchers have observed that outbreaks of certain pests are less in weed-diversified cropping systems than in weed-free fields which may be due to the fact that weeds camouflage crops from colonizing pests, making the crops less apparent to their prospective attackers. In other cases, it is because the alternative resources provided by weeds support beneficial arthropods. No doubt, weeds can stress crops, but substantial evidence suggests that farmers can enhance populations of beneficial arthropods by manipulating weed species and weed-management practices. A growing appreciation for the complex relationships among crops, weeds, pests and natural enemies is prompting many of the today's farmers to emphasize weed management over weed control.

8. Enhance plant defenses against pests

The first line of defense against insect pests is a healthy plant which can withstand the onslaught of insect pests and respond by mobilizing inbred mechanisms to fight off the attack. Natural defenses can be enhanced by improving soil and providing the best possible growing conditions, including adequate (but not excess) water and nutrients.

As plants co-evolved with pests, they developed numerous defenses against those pests. Some of those defenses have been strengthened over time through plant breeding, while others have been lost. Some plant defenses viz. spines, leaf hairs, tough and leathery leaves are structural defences whereas, others are chemical:

- *Continuous*, or *constitutive* defenses are maintained at effective levels around the clock, regardless of the presence of pests; they include toxic plant chemicals that deter feeding, leaf waxes that form barriers, allelopathic chemicals that deter weed growth and other similar defenses.
- *Induced* responses are prompted by pest attacks; they allow plants to use their resources more flexibly, spending them on growth and reproduction when risks of infection or infestation are low but deploying them on an as-needed basis for defense when pests reach trigger levels.

The most effective and durable plant defense systems combine continuous and induced responses. The plants being killed by a plant-eating insect or mite may respond directly by unleashing a toxic chemical that will damage the pest or obstruct its feeding. It may also respond indirectly, recruiting the assistance of a third party.

Many plants produce volatile chemicals that attract the natural enemies of their attackers. These signals must be identifiable and distinguishable by the predators and parasites which are helpful for the crop. Fortunately, plants under attack release different volatile compounds than the healthy plants. Crops, can even emit different blends of chemicals in response to feeding by different pests. Different varieties of the same crop or even different parts or growth stages of the same plant can release different amounts and proportions of volatile compounds. Leaves that escape injury also produce and release volatiles, intensifying the signaling capacities of damaged plants.

9. Management of soils to minimize crop pests

Agricultural practices that promote healthy soils are a pillar of ecologically based pest management. Good soil management can improve water storage, drainage, nutrient availability and root development which may, in turn, influence crop-defense mechanisms and populations of potential beneficial arthropods and pests.

In contrast, adverse soil conditions can hinder plants' abilities to use their natural defenses against insects, diseases, nematodes and weeds. Poor soils can cause plants to emit stress signals to potential attackers, heightening the risk of insect damage.

10. Integrated nutrition management (INM)

Nutrition management is one of the most important practices for high production system, but it may affect host-insect interaction. Insect behavior and life parameters are affected by environmental factors, such as temperature, moisture, habitat, morphological and chemical components of host plants, especially by the nutrients i.e. nitrogen, sugars, amino acids and semio-chemicals in host plants. Several studies have indicated the importance of host plant quality on herbivorous insects. Abiotic heterogeneity through crop nutrition can affect the susceptibility of plants to insect pests by altering plant tissue nutrient levels and morphology. Excessive and/or inappropriate use of inorganic fertilizers can cause nutrient imbalances and lower pest resistance. Nitrogen (N) content is regarded as an indicator of plant quality and one of the most important performance limiting factors of herbivores. Heavy applications of N fertilizer may not affect insect biology directly, but change the host-plant morphology, biochemistry and physiology, which can improve nutritional conditions for herbivores, thus playing a key role in modifying and reducing host resistance to them. An excess of nitrogen (N) or deficiency of potassium (K) can lead to higher accumulation of amino acids, which in turn can cause higher attack rate by sucking insects. Nitrogen limitation is well documented in insect herbivores, but phosphorus (P) limitation is poorly studied, although insect herbivores require not only N, but also P to synthesize their proteins. Phosphorus is required for ATP and nucleic acid synthesis (RNA and DNA), and thus protein production. Potassium (K) has a critical role in plant physiology. Potassium nutrition has a profound effect on the profile and distribution of the primary metabolites in plant tissues. There are multiple changes in metabolite concentrations induced by K including K dependence of metabolic enzymes, photosynthesis and long-distance transport. The primary metabolites such as soluble sugars particularly reducing sugars, organic acids and amino acids tend to increase in K deficient plants. It was reported that plant damage by insect is comparatively less in K applied plants due to reduced carbohydrate accumulation, elimination of amino acids etc.

The bibliographical data relating to all pests and diseases indicated a beneficial effect in 65 per cent and deleterious effect (increased disease or pests) in 28 per cent of cases. Of the 2449 reports, K application resulted in decrease of 70, 63, 33, 41, and 69 per cent in fungal diseases, insects and mites, nematodes, viruses and bacteria, respectively. It is interesting to note that K had a beneficial effect in 87 per cent of cases in low K soils and 66 per cent cases in soils sufficient or high in K. Similarly, the average reduction in severity of fungal diseases was four times greater on low K soils. Insufficient K causes a pale leaf colour which is highly attractive to aphids, which compete for assimilates and transmit viruses. Wilting, commonly observed with K deficiency, is another attraction to insects. Soil nutrients can influence the population dynamics of arthropod pests and their natural enemies; besides, earlier research has revealed that over fertilization increases the likelihood of pest outbreak in a subsequent crop of soybean [*Glycine max* (L.) Merr.], following winter wheat (*Triticum aestivum* L.). The effect of nutrient management practices was studied on incidence of insect-pests and productivity of soybean (*Glycine max* L.) under rainfed farming in Karnataka. It has been reported that there was no significant difference in the incidence of pod borer (*Helicoverpa armigera* Hub.) among the treatments; but, there was significant difference in plant damage caused by stem fly. It has been postulated that when plants are stressed by certain changes in patterns of weather they become a better source of food for invertebrate herbivores because this stress causes an increase in the amount of nitrogen available in their tissues for young herbivores feeding on them; and this may cause outbreaks of such phytophagous invertebrates. Scanty information is available on the effects of N, P and K on the feeding of insect pests in soybean field crops.

All these ten strategies (1 to 10) can be utilized in the most effective way towards achieving non-chemical management of noxious pests in agro-ecosystems. Farm scaping should be invariably followed under integrated farming systems. The quantum and type of flowering plant to be introduced in farm scaping should be known well in advance.

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16. INSECT PEST MANAGEMENT UNDER NATURAL FARMING

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Abstract: Natural farming has been accepted as the cardinal principal of agriculture by the Government of India after a lot of tinkering and resistance from the scientific fraternity. In general, there exists a little proportion of rational thinking among the scientists regarding the proper understanding of the scientific principles of the science of natural farming. Present juncture is akin to the era of beginning of “Green Revolution” in India with juxtaposed views of scientists and farmers regarding the possibility and ethics of chemical farming, a practice universally adopted by Indian scientists and farmers alike. It infact, reverting to the century old principles of traditional Indian farming system, practiced successfully till barely some fifty-five years ago that has fed not only the Indian subcontinent but also many other countries of the world. Natural farming is a perfect and time-tested science in unison with the Mother Nature. The major threat in the modern chemical farming system is the incidence of insect-pests and diseases that has reached epic proportion and application of any amount of the most toxic pesticides has failed to keep their population below economic injury levels. Analysis of the crisis scientifically and clearly reflects catastrophic “imbalance” of the “balance of nature” or in simple words, disruption of complex food chains and food webs through the near elimination of the most useful 3-Ps viz. parasitoids, predators and pathogens. It is important to “fourth P” i.e. pollinators which are one of the biggest casualty of the modern scientific agriculture. It is therefore, of utmost importance to give at least the idea of natural farming a decent chance as was hesitantly given to the era of green revolution. Natural farming shall certainly become the cardinal principal of modern agriculture. The basic principles of insect-pest management under natural farming are presented here.

Introduction

Humans' rightly acknowledged insects as the most successful taxa on the planet earth but his greed has brought him in direct conflict with them resulting in decimation and poisoning of ecologically stable food chains and food webs. Insects have retaliated with ferocity and most of them have turned up as giants with multiple resistance to almost all groups of pesticides. The so called scientific management efforts of human beings through increased doses of so called “novel pesticides” and further the cocktail of combination pesticides have utterly failed. Besides ecological disasters, multiple increases in the cost of crop production brought an untold misery to the farmers. Present day instable crop ecosystems in guise of “advanced science” and so called integrated pest management (IPM) are inherently antagonistic and in conjugation with destabilizing anthropogenic activities. It has resulted in local as well as global catastrophic ramifications in the form of global warming and climate change.

How insects turned pests and became man's dreaded foes?

Entomologists took pride in designating a miniscule proportion of the insects as pests. However, against all scientific laws, they employed all the arsenals at their command against these harmless insects, turning hitherto beneficial insects into their dreaded foes. Extreme exploitation of potential management tactics and technological advances at genetic and molecular level failed to tame these pests who rebounded with alarming veracity at each of man's newer interventions. Resultant exorbitant increase in the cost of production tuned farming into a loss making enterprise. Now, the farmer's growing distress and suicidal tendencies have been linked to the use of toxic agrochemicals! System analysis clearly points to man's own defiance of the principals and definition of IPM. The much touted national policy of IPM adopted since 1985, failed the test of field adoption. Three pillars of IPM *viz*., ecological compatibility, economic viability and social acceptance lack adoption before initiation of pest management programme. Overall, the present pest management strategies lack holistic agro-ecosystem approach and IPM has purely been replaced with chemical control strategy. Farmer's near total dependence on chemical alternatives have manifested in multiple ecological, economical and health problems. The resultant increasing list of Indian sunshine products facing international ban due to the presence of toxic residues include honey, mango, basmati rice, wheat etc. is a testimony to the system failure.

Organic farming

An alternate approach of organic farming where, nutrients as well as plant protection measures were substituted by organic (non-chemical) sources found favour with a section of farmers and consumers but it too is fraught with the same lacunae and in no way restore the system to stability. Moreover, it eventually increased the cost of production of farmers.

Organic and natural farming - the way forward

As per basic ecology principles, the pest problem arise as a result of disruption of "balance of nature" and its restoration eliminates the problem. So, the ecosystems closer to the natural/ forest ecosystem are unlikely to have serious pest problems while highly degraded agro-ecosystems are prone to the disasters. "Natural farming" system advocates holistic approach of a cropping system based on the principles of nature proposed by Padamshri Subhash Palekar seems an ideal one. He suggests multiple and multi-layered cropping system; nutrient supply through cow based products (cow dung and urine); utilization of crop residues for nutrient recycling; irrigation only to create moisture in soil; creating conditions congenial to the development of earthworms and symbiotic and asymbiotic soil micro flora; ultimately creating conditions for the formation of humus and management of pests through botanicals and cow based products. The question arises whether it is possible to maintain similar productivity level and pest control in agro-ecosystems and natural farming, devoid of chemical fertilizers and pesticides and needs to be considered under two dimensions:

1. Meeting high nutrient demand of high yielding crops: In organic farming, the chemical source of nutrients is through farm yard manure (FYM) in huge quantities (10-12 tonnes/acre) and is supplemented by vermicompost. Other gametes are green manuring, use of commercially available cultures of nitrogen fixing bacteria (*Rhizobium, Azotobacter*, blue green algae, etc.), potassium solublizing bacteria (PSB) and other nutrients. The insect pests and diseases are managed by the application numerous fungus/bacterial cultures (*Trichoderma virde*, *T. harzianum* etc.), botanical pesticides (neem kernel or oil based products, etc.) and various microbial pesticides (*Metarrhizium* spp., *Beauveria bassiana*, NPV etc.).

Natural farming encompasses holistic approach that "mother earth and its associated environment in itself is a self sustaining ecosystem" since all essential nutrients required by plants are present in the air or soil around the plants. Three major components namely, carbon, hydrogen and oxygen are abundantly and freely available in the atmosphere and water while carbon dioxide is directly taken by the plants from air. Water too is directly taken up by the plants through its roots that are broken down into oxygen and hydrogen during the process of photosynthesis in the green leaves. Plants take substantial quantities of three major nutrients- nitrogen, phosphorus and potash from soil. Nitrogen comprises 78.6% of the air and over an acre astonishing amount of 32,000 tons is available but plants cannot take it directly. It is either fixed in the root nodules of leguminous plants by symbiotic nitrogen fixing bacteria or in the soil near the roots of non-leguminous plants by non-symbiotic bacteria like *Azatobactor, Gluconacytobactor* etc. and is taken up by the plant roots. Phosphorus too is present in the soil in the non-available form. PSB convert it into soluble form that is easily taken up by the plant roots. Similarly, potassium and other minor and micro nutrients too are made available to the plants by an array of soil dwelling beneficial bacteria.

2. Management of pests (weeds, insects, diseases, etc.): Entomologists and ecologists teach why pest problem arises in agro-ecosystems and not in natural ecosystems. In a natural ecosystem, these biotic and abiotic forces maintain population densities of the organisms at sustainable level, never allowing them to be either too high or low. However, in agro-ecosystems where human interventions have degraded these population balancing forces, the pest problems abound.

Modeling of new/novel insecticides on natural or botanicals: Many of the novel and the most widely used insecticides are modeled on indigenous botanical resources. Nicotine, the basic ingredient of tobacco which has a wide range of effects on a range of pests was the prime product used by the farmers in pre-synthetic pesticide era along with other botanicals. Neonicotinoids primarily modeled on the same principle of nicotine are now the world's largest used insecticides. Similarly, many novel insecticides based on these natural products or derived from soil dwelling organisms like actinomycetes (spinosads) etc. are now widely used in agriculture.

Can organic and natural agriculture feed the world? Global scientific evidence reiterates unambiguously that "organic farming can feed the world population of 9 billion by 2050 from existing land" and has come from world scientific community of FAO and many other countries (Muller *et al.*, 2017). The organic agriculture can feed the world with lower environmental impacts, provided we reduce food waste and arable land to produce animal feed with less consumption of animal products and greater use of nitrogen-fixing legumes. A 100% conversion to organic agriculture needs more land than conventional agriculture but reduces N-surplus and pesticide use. A study by the Indian Council for Research on International Economic Relations (Mukherjee *et al.*, 2017) estimates the present world market of organic products at US$ 85 billion. They reported that traditional Indian agriculture is organic by default. International market of organic products is presently growing by 14% and future projections are at 20% and India is leader in area under organic farming (50 million ha) and number of organic products are exported.

Different organic and natural farming approaches: Many alternate therapies/approaches are practiced in India namely, *Panchgavya / Dashgavya krishi*, *Angara krishi*, *Sendriya krishi,* Agro-ecological farming, *Phoonkmaar kheti,* Sustainable farming, Biodynamic farming, *Nadep, Rishi krishi, Agnihotra krishi, etc.* The other form is zero budget natural farming (ZBNF), now renamed as Subhash Palekar Natural Farming (SPNF).

Insect pest management in natural farming

In true and persistent natural farming, near natural environment is supposed to promote diverse food chains and webs thus, shall not have any insect-pest problem. As it is impossible to maintain such natural environment in a heterogeneous agro-ecosystem of a pluralistic village, some flare ups due to migration and other factors are likely to occor. They are managed with botanical/natural insecticides prepared easily by the farmers from local resources at almost negligible cost (zero budget) or are supplied as ready to use formulations. Palekar (2010, 2011) and Chaudhary (2017) detailed the procedures of preparation and application of many concoctions of natural insecticides. They emphasized two-pronged strategy firstly, of initial protection through seed treatment and secondly, their use as spray.

A. Seed treatment: Seed treatment with pesticides has emerged as an efficient and cost-effective means of protection in many crops. The flip side is large scale killing of honey bees and wild pollinators with neonicotinoids seed dressing in large parts of the world. Severity of loss has resulted in their ban in the European Union (EFSA, 2018). In chemical farming, seed treatment with three types of chemicals is recommended i.e. insecticides in the evening, fungicides in the morning, followed by smearing with culture (ABC) that provide protection against limited numbers of soil dwelling insects and pathogens for a short period. Although the cultures partially add to the spectra of nitrogen and other nutrient fixing bacteria but their large populations get eliminated in chemical enriched environment.

i) *Beejamrit* preparation and application: In natural farming, *Beejamrit* not only provide the safest alternatives as seed treatment against insect pests and diseases but also add an array of beneficial micro flora to the soil (Palekar, 2010, 2011). In a drum or old pitcher add 5 kg cow dung, 5-liter cow urine, 50 g lime, 20-liter water and a handful of soil from an undisturbed place of field like bund or under a tree. Mix the ingredients well with the help of a wooden stick and cover with a jute cloth.

Further, mix and stirr them every morning and evening with the stick for a period of 2 minutes by stirring in clock wise. After two days, the *Beejamrit* is ready for treating 100 kg seed. In the evening, spread the seeds to be treated on a tarpaulin or take them in an old drum or pitcher and add required quantity of *Beejamrit*. For cereal crops, take the seed in the middle of the palm and treat by pressing them hard with the hands. For pulse crops, lightly massage the seeds with the fingers so that a layer of *Beejamrit* gets smeared on the seed coat. Allow the seed to dry overnight and sow in the morning.
For treating 50 kg wheat seed, 15 liter of *Beejamrit* is needed. In the transplanted crops like paddy and vegetables, dip the seedlings in *Beejamrit* solution for 15-20 minutes and allow it to dry before transplanting. If the seeds are already treated with the chemical insecticides, they shall be first washed before application of *Beejamrit.* For sugarcane about 35-40 q seed is required for planting one acre of sugarcane with two or three budded setts. Take *beejamrit* in a wide tank or tub, dip buds for 15-20 minutes and allow drying up in shade for further 15-20 minutes before planting.

***ii) Jeevamrit*:** In natural farming, nutrition through chemical fertilizers is prohibited and it is provided through cow dung and urine based formulations. One gram dung of indigenous cow is reported to possess 300-500 crore ($3x10^9$) microorganisms (Palekar, 2011) and through *jeevamrit* 10 kg cow dung is added along with 10 liters of cow urine initially, that too contains substantial number of microbes. During the three day period of fermentation their numbers multiply enormously and on its application to the soil through irrigation water, it acts as a culture, multiplying continuously. This enormous mass of beneficial microbes makes available the nutrients to the plant roots. Microorganisms like *Pseudomonas, Trichoderma* spp. and host of others inhibit the growth of soil borne pathogenic microorganisms and insects thus, managing their populations.

Method of preparation: In a tank take 200 liter of water and add all the ingredients. Mix properly, cover with a jute cloth and place in shade for 3 days. Each morning and evening, mix it for 2 minutes by rotating in clock wise direction with a stick. After 3 days, *jeevamrit* is ready and it can be applied up to 7 days of preparation @ 200 liter per acre along with irrigation water.

B. Insect pest management using natural insecticides as spray: The information on Table 16.1 summarizes control of different groups of insects based on their feeding habit/niche by these natural formulations.

Table 16.1: Natural insecticides and their efficacy in management of different groups of insect pests

	Natural insecticides	Effective against insect-pest
1	Neem paste	Repellent against a wide range of insect pests
2	*Neemastra*	Sucking pests, mealy bug and young caterpillars
3	*Brahmastra*	Sucking pests, pod borers and fruit borers but does not control internal borers
4	*Agniastra*	Sucking pests, pod/fruit borers and internal borers
5	*Dashparni ark*	Sucking pests, internal borers and difficult to control pests

Basic common guidelines to prepare these formulations, their ingredients are enumerated below:

1. *Neem* paste: It is based on neem, *Azadzirachta indica* also known as the "pesticide tree". Neem oil extracts contain nearly 140 compounds out of which azadirachtin, a nortriterpenoid, belonging to lemonoids is the most important biological component that has shown some sensational insecticidal, fungicidal and bactericidal properties with divergent modes of action. It acts as insect growth regulator, antifeedants, repellent, ovipositional deterrent and affect insect vigour, longevity, fecundity and is recommended against more than 500 insects. Based on traditional indigenous knowledge, *neem* has multiple uses in natural farming. The basic formulation is "neem paste", for its application on the plant trunks. In a drum add 50 liters water, 20 liter cow urine, 20 kg cow dung and 10 kg paste of neem leaves and twigs. Mix the ingredients well and keep it covered for 48 hours and stir regularly. It is ready for use after 2 days with an expiry period of 7 days. Use neem paste once in each quarter of the year.

2. *Neemastra*: In a drum, take 200 liter water, 10 liter cow urine and 5 kg cow dung. Prepare a paste of 10 kg neem leaves along with branches and add to the drum. Mix the ingredients and keep it in the shade for 2 days for fermentation. Now filter the solution using muslin cloth and store it for future use up to a period of 6 months. It should be sprayed @ 200 liter solution per acre crop without dilution. Avoid use during crop flowering period to save honey bees and other pollinators.

3. *Brahmastra*: In an iron drum, take 100 liters of water and 30 liter cow urine and to it, add 2 kg leaf paste of the any each of five plants (total 10 kg). Make a paste and mix in the solution. Cover the mixture, heat slowly till one boil and allow it to cool for 48 hours. Filter and store it in a cool dry place. It can be used as spray up to a period of six months at 6-8 liters per acre in 200 liter of water.

4. *Agniastra*: In an iron drum, take water, 20 liter cow urine and to it add 2 kg paste of neem branches and leaves. and 500g each of tobacco and paste of hot green chillies and 250g/ garlic paste. Slowly heat the mixture till one boil while keeping it covered and allow it to cool for 48 hours. Filter and store in a cool dry place. It has an expiry period of 3 months and for one acre, *Agniastar* should be used (6-8 liters) for one acre mixed in 200 litres of water.

5. *Dashparni ark*: It is prepared using three tiers of products i.e. base of cow dung and urine fortified with botanicals. As the name indicates, it is superimposed with concoction of leaves of at least ten locally available plants that exhibit insecticidal properties. In a drum, take 200 liter water, 20 liter cow urine and 2 kg cow dung. Cover it with a jute cloth and leave it in shade for 2 hours, and to it add 500 g each of turmeric powder, and ginger paste,10 g asafoetida powder. Mix the contents, cover it and incubate it for 24 hours. Next morning add 1 kg tobacco powder, 1 kg hot green chilly paste and 500 g garlic paste and leave it for another 24 hours. On third day, add 2 kg leaves each of any of these five plants viz. neem, castor, jack fruit, *belgiri*, *dhatura* and *karanj* and 2 kg leaves each of any five plants amongst following ones viz. basil, *aak*, mango, marigold, pomegranate, *arjun, guava, papaya,* ber*, gudahal,* bitter gourd*, kaner, glo, chirayata* or any other locally available plants. Thereafter mix it properly and allow it to ferment it for 30-40 days. It is observed that bad stink emanates from the mixture due to fermentation process. So to cover your nose with a clean cloth. The ready to use *dashparni ark* may be filtered with muslin cloth and store in a cool dry place. Use 6-8 liter *Dashparni ark* mixed in 200 liter water for controlling internal borers and pests that are very difficult to manage. It has an expiry date of 6 months.

6. Butter milk: In a drum take 200 liters water and to it add 20 liter *jeevamrit* and 5-10 liters of 5-10 days old butter milk. Mix the contents and apply it immediately. Generally, it is recommended as a fungicide but also helps in the management of insect pests.

7. *Jeevamrit*: *Jeevamrit* is additionally applied as a spray in the standing crops after filtering it with muslin cloth. The information about the amount and frequency of *jeevamrit* application in different crops depending upon their maturity period is summerized in Table 16.2.

8. Mealy bug management product: Pods of indigenous "*babool*" plant are effective for the management of young stages of mealy bugs. Collect and grind the pods along with the seeds. In a container take 5 liter of water and to it, add 200 g *babool* powder and keep it covered for 24 hours. Filter it and use as spray in 200 liter of water.

Table 16.2: Amount and time of application of *jeevamrit* in different crops

Crop maturity period (days)	First spray 21 days after sowing	***Jeevamrit* concentration in sprays (%)**					
		1	**2**	**3**	**4**	**5**	**6**
60-90	Subsequent application 21 days after each spray	5	7.5	Buttermilk	-	-	-
90-120		5	7.5	10	Buttermilk	-	-
120-135		5	7.5	Buttermilk	10	Buttermilk	-
135-150		5	7.5	Buttermilk	10	10	Buttermilk
165-180		5	7.5	Buttermilk	10	10	Buttermilk

The microbial base of cow dung and urine synergizes well with insecticidal properties of large array of plants and their products to provide effective management of almost all the groups of insect pests. Their ability to protect beneficial organisms, environment friendliness and absence of negative impacts of chemical insecticides make natural formulations an ideal choice for modern intensive agriculture besides adding immense value to the food and food chains.

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17. NUTRIENT, INSECT-PEST AND DISEASE MANAGEMENT IN NATURAL FARMING

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Abstract: In the modern agriculture, the use of chemical fertilizers and pesticides has reached an alarming stage and has polluted every component of ecosystem including soil, water and air. Application of even higher amounts and rates of any of toxic pesticides has failed to keep the population of insect-pests and pathogens below economic injury levels. It is therefore, imperative to look for an alternative farming system that can take care of the ill effects of chemicals, and protect Mother Nature from all sorts of toxins. Natural farming can be a viable solution to ensure food security by reviving Indian agriculture in environmentally safe way and to release farmers from debt cycle. The Natural farming philosophy is based on the principle of working in harmony with nature and natural cycles for producing safer and healthy food while maintaining the health of soil, humans, and livestock. Natural farming has been accepted as the cardinal principal of agriculture by the Government of India after a lot of resistance from different sections of the society. In this farming system, locally available material is used to prepare on- farm products that are used to manage nutrients, pests and diseases in crops and the dependence on external inputs is negligible. It holds the promise of enhancing farmers' income besides offering many other benefits, such as restoration of soil fertility and environmental health, and mitigating and/or reducing greenhouse gas emissions. Natural farming minimizes human labour and encourages farmers to use local varieties of seeds, and native varieties of vegetables, grains, pulses and other crops. In times to come, natural farming shall become the fundamental principle of modern agriculture. However, multilocational studies are needed to assess and authenticate the long term effects of natural farming on soil, land and environment health before this system can be scaled up and promoted country-wide.

Introduction

Natural Farming (NF) is a unique chemical-free, agroecology-based diversified farming method, which integrates crops, trees and livestock, allowing functional biodiversity. This climate resilient, safer and low-cost alternative system of farming endeavours to promote agroecology and adopt low cost agricultural practices wherein, all vital inputs are obtained from the field itself and nothing is introduced from outside. Under natural farming, only 20 % of water is utilized for irrigation as compared to traditional farming techniques. Natural farming is a holistic method whereby farmers are discouraged to buy market based inputs like chemical fertilizers, chemical pesticides etc. which are primarily considered toxic to agriculture. It persuades farmers to grow healthy plants in healthy soil with friendly earthworms within low budget. The Natural farming philosophy is based on the principle of working in harmony with nature and natural cycles for producing safer and healthy food while maintaining the health of soil, humans, and livestock. The concept was first put forward by a Japanese farmer and philosopher Masanobu Fukuoka (1913–2008), and described in detail in his famous book "The One-Straw Revolution", also known as "the Fukuoka method", "the natural way of farming," or "do nothing farming" (Fukuoka, 1987). This approach promotes the use of local hardy varieties and landraces of field crops, vegetables, and other crops without application of fertilizers and pesticides. However, on- farm produced products are used to manage nutrients, pests, diseases, and weeds in crops.

In India, Zero Budget Natural Farming (ZBNF), now Subhash Palekar Natural farming (SPNF) was originally introduced by an agriculturist Sh. Subhash Palekar in the mid-1990s, who has been conferred one of the highest civilian awards of country, Padma Shri in 2016 for promoting this farming technique. This farming requires absolutely no monetary investment for purchase of key inputs like seeds, fertilizers and plant protection chemicals from the market. Also, the reliance on hired labour is reduced to bare minimum as the method discourages intercultural operations. Only a native breed of cattle is required which in any case forms an essential part of farming families in rural areas. The farmer can produce his own seed or he may use seeds available with other farmers. The whole philosophy behind this system is to make the farmer self-dependent so that he is freed from the clutches of money lenders and market dispensed high cost inputs (Devvrat, 2018). It restores soil fertility and soil organic matter and promotes climate-friendly agricultural system, thus help in attaining sustainable agriculture with the reduced carbon footprint.

Quite a few states including Andhra Pradesh, Himachal Pradesh, Karnataka and Maharashtra have been enthusiastically shifting towards this model. The method promotes soil aeration, minimal watering, intercropping, bunds, soil mulching and dejects intensive irrigation and deep ploughing.

Natural farming is self-nourishing and symbiotic in nature. Over many years of devoted research, Palekar (2005) revealed that:

1. Only the dung from local Indian cows is effective in the re-enrichment of barren soil and that from Jersey and Holstein cows is not as effective as the local ones. In case of inadequate availability of dung from local cows, dung from bullocks or buffaloes may be used.
2. Dung and urine of the black coloured *Kapila* cow is believed to be miraculous.
3. To get the most out of cow dung and urine, ensure that the dung is as fresh as possible (upto 7 days old) and that the urine is as stale as possible (more than 5 days old).
4. Ten kg local cow dung per acre per month is required. On an average a cow deficates 11 kg dung per day hence, dung from one cow is sufficient to fertilize 30 acres of land per month.
5. Urine, jaggery and pulse (dicot) flour can be used as additives.

Why Natural Farming?

In the green revolution era, use of high yielding varieties, chemical fertilizers, synthetic plant protection chemicals like fungicides, insecticides, and herbicides were used extensively to increase the productivity of wheat and rice crops which were responsive to high inputs. Hence, the pesticides emerged as one of the essential agro-inputs to augment crop yields. However, scientific investigations and facts have signified a number of perils associated with the imprudent use of such chemicals *viz*. resistance in pests and pathogens, killing of various beneficial organisms like fishes, birds, wildlife, pollinators and microbes, poisoning of agricultural farm workers, contamination of soil, air, surface and ground water, biomagnification of toxicants in food chains, residues in food, feed stuff etc. In addition, high labour wages, volatile market prices, unpredicted monsoon extremes, large number of farmers suicides, rising environmental concerns, and change in consumers' preference towards safety food compels to ponder of an alternative farming system that is sustainable, low cost, and at the same time, environment friendly and enhances farm income. In this direction, natural farming seems to be a viable and sustainable option. The idea is to let nature play a dominant role to the maximum extent possible.

Advantages and Disadvantages of Natural farming

Advantages:

- Natural Farming restores the soil damaged by chemicals, herbicides and machines.
- It follows the law of nature while respecting the rights of crops and livestock.
- Diseases and insect-pest attacks are prevented rather than cured with chemicals.
- Healthy livestock is reared instead of making animals healthy by administering hormones and antibiotics.
- The natural farming crops and orchards offer greater resilience to climatic extremities.
- The products obtained through natural farming offer better nutritional quality and taste with no harmful residues.
- The highest benefit is that all the products are prepared by the farmers themselves using only locally available natural materials and no materials are bought from the market.
- Natural farming is a powerful solution to the debt crisis among Indian farmers and reduces farmers' dependence on loans to purchase inputs they cannot pay for.
- Long-term adoption leads to clean soil and water and ecological recovery.

- Use of inter/mixed cropping enhances returns of farmers.

Disadvantages:
- The opponents of this scheme consider it as more of naturistic and philosophical farming technique of farming rather than being rational and scientific.
- It is rather new concept that needs scientific validation from the farmers, scientists and policymakers across the country.
- There are no dedicated markets to sell the products.
- Takes long conversion period and is practiced in fewer parts of India on less area.

Four pillars/wheels of Subhash Palekar's Natural Farming

1.Jeevamrit: *Jeevamrit* is claimed to be a panacea for natural farming.It is fermented microbial culture of native species of microbes and organisms prepared from mixture of dung and urine of indigenous (*desi*) cow, pulse flour and undisturbed soil. During the 48 hour fermentation process, the aerobic and anaerobic bacteria present in the cow dung and urine multiply as they consume organic ingredients (pulse flour). This culture acts as a catalytic agent to promote the activity of beneficial micro-organisms and native species of earthworms in the soil and also increases the quantity of organic carbon in soil. This makes the essential nutrients present in soil, available to the plants which were not available earlier. The mixture maintains fertility status of soil and also helps in preventing the attack of various fungal and bacterial diseases. *Jeevamrit* can be applied to the crops twice a month as foliar sprays @10%.

2. Beejamrit: It is prepared from dung and urine of *desi* cow and burnt lime. It is used for the treatment of seeds, seedlings and other planting material. It protects the plants from the attack of seed and soil borne diseases and plant roots from the attack of fungus. The treated seeds germinate faster with higher germination capacity. The plants have more tolerance to adverse climatic conditions, insect-pests and diseases. *Beejamrit* (200 ml/kg) can be coated on to the seeds of any crop with hands, seeds are dried well and used for sowing.

***3.* Mulching (*Achhadana*)**: Mulching refers to covering the upper layer of soil with mulch to reduce evaporation. It builds congenial micro-climate i.e. 25°C to 32°C temperature and 65 to 72 per cent moisture, in soil for better development of micro-organisms. It increases humus content, maintains warmth in soil, protects upper layer of soil, conserves soil moisture, increases the quantity of essential nutrients and microbial population in the soil and suppresses weeds. The mulch can be *soil, straw or live mulch. Soil mulch* protects the top layer of soil during cultivation and does not destroy it by tilling. It promotes aeration and water retention in the soil. *Straw mulch* is the dry organic material, which decomposes to form humus through the activity of soil biota which is activated by microbial cultures. It is the dried biomass waste of previous crops, the dead material of any plants or grasses etc. *Live mulch (symbiotic intercrops and mixed crops)*: Multiple cropping patterns of monocotyledons and dicotyledons are followed in the same field with the intent to supply all essential elements to the soil and crops from different crops eg. legumes are nitrogen fixing plants whereas, monocots like rice and wheat supply other elements like potash, phosphate and sulphur. Hence the association is symbiotic and both are benefitted from each other in the process.

***4.* Moisture (*Whapasa*)**: Roots of plants need water vapour instead of water. *Whapasa* is the state where air and water molecules co-exist in the soil. When *Jeevamrit* and *achhadana* are added in the soil, *whapasa* is created which leads to the faster production of humus in the soil. It leads to better water management in the soil which prevents lodging of plants in rainy season and wilting in summer season.

Principles of Natural Farming:

(i) **Intercropping/Multicropping:** In natural farming, intercrops/mixed crops are grown along with the main crops. Such crops supply nitrogen, phosphorus, potash and other important nutrients to the main crop. The nitrogen fixing bacteria like *Rhizobium*, *Azotobacter*, *Azospirillium* etc. present in the root nodules of these crops aid in proper development of plants. The main crop is also sheltered from insect-pests. The chief purpose of growing inter/mixed crops is that any cost incurred on main crop will be compensated for by the income from these crops. It is a noble way to minimize risks to the farmers who will be able to enjoy the continuity of yield and cash round the year.

(ii) **Contours and bunds:** Contours and bunds are made in the field to collect rain water which keep the land moist and enable the availability of water to the plants for a longer period and help in proper drainage of water in fields during rainy season.

(iii) **Indigenous species of earthworms:** Palekar advocates the revival of local deep species of earthworms through increased organic matter. The activity of such earthworms can be promoted by mulching which creates dark environment that builds micro-climate in soil suitable for the activity of earthworms. Earthworms augment the humus content in soil leading to improved nutrient availability, enhanced drainage and a more stable soil structure, all of which facilitate crop productivity. When earthworms eat, they leave behind castings that act as precious source of fertilizer.

(iv) **Cow dung and cow urine:** Natural farming is completely cow-based. One gram dung of indigenous (*desi*) cow contains 300 to 500 crores of beneficial microorganisms as compared to foreign breeds having only 78 lakh beneficial microorganisms. The activity of earthworms is also more in soil treated with dung and urine of *desi* cow which increases the fertility status of soil with their castings. There are 16 major nutrients in *desi* cow dung and plants need these 16 nutrients for their suitable growth and development. Hence dung and urine of *desi* cow is excellent for natural farming.

(v) **No use of synthetic chemicals**: In natural farming, nutrients, insect-pests and diseases in plants are managed by the farmers with natural products prepared easily by them from local resources at almost negligible cost. As per Palekar, these natural preparations will supply essential nutrients to the crop and keep the crop free from insect-pests and diseases and concurrently take care of deleterious effects of chemical fertilizers and pesticides. Palekar has detailed the procedures of preparation and application of these man-made products of natural fertilizers/pesticides. He has emphasized on two pronged strategy *i.e*. their use as seed/soil treatment and as sprays.

(vi) **No use of vermicompost**: Mr Palekar is against the use of vermicompost, which is the mainstay of typical organic farming as it introduces the exotic earthworm species, the European red wiggler (*Eisenia foetida*) to Indian soils. It is claimed that these worms are threatening as they absorb metals and contaminate groundwater and soil. According to Palekar, deeper soil has its own indigenous earth worm species which can efficiently enhance soil fertility when any organic matter is added to the soil and there is no particular need of use of external vermicompost.

(vii) **Ploughing:** Deep ploughing is avoided as it leads to rise in soil temperature to a level that the carbon from the soil starts vapourizing; this forbids humus production in soil decreasing its fertility level.

(viii) **Water management:** In natural farming, the plants are irrigated from some distance so that only 10 per cent of water is used; remaining 90 per cent is saved. The root length and stem width of plants is enhanced, that increases the overall plant height which ultimately boosts up the crop production.

ix) **Plant direction:** The plants are grown in north-south direction so that they may trap sunlight for longer span of time. Wider plant to plant spacing triggers better growth of each plant by enhanced interception of sunlight and the plants become healthier and deter the attack of insect-pests and diseases. The plants accumulate nutrients in desired quantities and the production increases by 20 per cent.

(x) **Microclimate:** Under natural farming, mulching helps to maintain optimum conditions like 65 to 72 per cent moisture, 25 to 32 ºC air temperature, darkness, humus and warmth in soil.

(xi) **Local seed/varieties:** Indigenous seeds/varieties are adopted under natural farming and use of hybrids is discouraged. Such varieties require low amount of nutrients, and are less susceptible to insect-pests and diseases as these are well adapted and evolved locally under the prevailing diseases and insect pests and possess characters of wild races.

I. Natural Products for Nutrient Management

***1. Jeevamrit/Jeevamrutham*:**It is a fermented microbial culture that promotes the activity of beneficial microorganisms and earthworms in soil which help in making unavailable essential nutrients in soil, available to plants. It also increases the quantity of organic carbon in soil and helps to prevent fungal and bacterial plant diseases. *Jeevamrutham* is made of two Sanskrit words – *Jeeva* and *Amrutham*. The word "*Jeeva*" means a living being and "*Amrutham*" stands for elixir of life which has the capability of extending life.

Itincreases the proportion of beneficial microorganisms in the soil that make the nutrients available to the crop which can act as efficient plant growth promoter and thus enhances the productivity of the crop. It increases the count of earthworms in soil which is beneficial for soil fertility. *Jeevamrit* is one of those organic fertilizers having large number of nutrients like nitrogen, phosphorus, calcium, and other micronutrients.

Preparation Method: In a large plastic barrel, about 200 litres water, 10 kg dung of *desi* cow, 10 litres urine of *desi* cow, 2 kg *gur*, 2 kg gram flour, 100 g soil around the bark of big tree are added and stirred with a wooden stick. This solution is kept under shade for 2-3 days to allow fermentation. Daily the solution is stirred twice for 2 minutes with a wooden stick in clockwise direction and then covered with a jute bag. The solution is strained through a cloth and stored and used within 7 days. Freshly prepared *Jeevamrit* is acidic in nature with a pH of 5.63 and electrical conductivity of 0.23 dS m and calcium content of 66.4 ppm. During application of *Jeevamrit*, there should be enough moisture in the land.

In field crops, it is applied once or twice a month @ 200 litres per acre along with the irrigation water. *In fruit crops,* it is applied in soil at noon under the shade of tree @ 2 to 5 litres around the tree trunks. For foliage application, it should be applied @ 10 %.

***2.Ghanjeevamrit/Ghanjeevamruthum*:** It is the source of millions of beneficial microorganisms. It can be used in rainfed areas for better crop growth.

Preparation Method: About100 kg dung of *desi* cow, 5 litres urine *of desi c*ow, 1kg pulse flour, 1 kg *gur*, and 500 g of virgin soil around the bark of big tree are mixed and kneaded well. The mixture is covered with jute bag for 4 days and moistened by sprinkling water in it. In winters, the mixture is kept covered for 7-14 days. When the mixture becomes thick, laddoos are prepared and cow urine is added, if needed. The laddoos are dried in shade and can be stored upto one year.

Ghanjeevamrit is applied @ 200 kg/acre at the time of sowing. The laddoos of *Ghanjeevamrit* are placed around the transplanted seedlings and covered with dry grass. These can also be kept near the fruit plants to help the nutrients reach upto the root zone.

Few investigations on nutrient management under Natural Farming

- In experiments conducted at Zero Budget Natural Farm of Deptt of Organic Agriculture and Natural Farming, CSK HPKV, Palampur; SPNF recommendation + *Jeevamrit* sprays at 7 days interval recorded highest fruit yield of okra (23.99 q/ha) and seed yield of intercropped soybean (10.29 q/ha).
- Drenching of *Jeevamrit* @10% at weekly intervals recorded the highest fruit yield (610.75 q/ha) of tomato in naturally ventilated polyhouse.
- *Ghanjeevamrit* @ 1000 kg/ha as basal dose + *Jeevamrit* sprays @ 10% at 14 days interval resulted in the highest yield of cucumber fruits (685 q/ha) in naturally ventilated polyhouse.
- Application of *Ghanjeevamrit* @1000 kg/ha + *Jeevamrit* (10%) sprays at 14 days interval recorded the highest yield of peas (variety" PB-89) i.e. 129.67 q/ha over other treatments

including control (39 q/ha) under naturally ventilated polyhouse conditions.

- Vermicompost @ 10t/ha + Biofertilizer (*Azospirillum*+ PSB) + spray of *jeevamrit* 10% at 5 days interval+ other sprays as per SPNF and *Ghanjeevamrit*@ 500 kg/ha + 500 kg/ha at 1 month interval + first spray of *jeevamrit* at 2 weeks + consequent sprays at 5 days interval, registered the highest fruit yield of capsicum i.e 358 q/ha and 316 q/ha, respectively over control (187.67 q/ha) under naturally ventilated polyhouse condition at Model Organic Farm of the University.
- According to Kasbe et al.(2009), higher nutrient status of *jeevamrit* formulation (2500 l/ha) resulted in profused growth i.e. higher dry matter accumulation and yield parameters in aerobic rice.
- Kaur et al. (2021) recorded significantly higher wheat grain yield (3117 kg/ha) with *Jeevamrit* application @ 20% at 2 weeks interval which was at par with application of *Jeevamrit* @ 10 % at 2 and 3 weeks interval and *Jeevamrit* @ 20 % at 3 weeks interval and check i.e. vermicompost @ 10 t/ha + 3 sprays of vermiwash @ 750 l/ha).
- In Japan, natural farming improved bulk density, pH, electrical conductivity, urease activity, and nitrate reductase activity in topsoil; similar trends were observed in deeper soil in cabbage crop. Natural farming increased microbial abundance compared to conventional farming (Liao et al. 2019).
- Application of *Ghanjeevamrit* + *Jeevamrit* + mulching significantly increased the seed yield of black gram over absolute control by 61.4 and 233.1 per cent during 2019 and 2020, respectively and recorded higher net returns of Rs. 64206 per ha over other treatments (Nasratullah, 2021).
- Effect of a favourable micro-climate offered in the Subhash Palekar Natural Farming (SPNF) system in comparison to the ongoing Conventional Farming (CF) in cabbage was enumerated. The SPNF attracted relatively more natural enemies, with the occurrence of *Diadegma semiclausum* (Hellen) as an additional important bioagent. The increase in soil micro-flora and soil enzymes activity was significantly higher in SPNF than in CF system (Rana et al. 2021).
- *Ghanjeevamrit* + *Jeevamrit* + mulching resulted in production of significantly highest available nitrogen and NPK content and uptake, viable microbial count, dehydrogenase activity and seed yield of wheat (1767.3 kg ha^{-1}) and gram (734.1 kg ha^{-1}) (Choudhary et al. 2022).
- At CSKHPKV, Palampur; ZBNF + minimum tillage +mulch treatment with or without intercropping showed higher soil moisture content, emergence count, emergence velocity, relative leaf water content, root parameters, yield and water use efficiency of rainfed maize as compared to the treatments with conventional tillage during the two-year study (Jaswal et al. 2022).

II Natural Products for Insect-Pest Management

1. *Beejamrit/Beejamruthum*: Most of the diseases, insect-pest infestation and other disorders in plants are seed and soil-borne. So, it is important to treat seeds, seedlings or other planting material with *beejamrit* before sowing to prevent seed and soil-borne diseases and insect-pest infestation in plants. *Beejamrit* increases germination capacity of seeds. It leads to uniform seedlings and faster development of roots. Plants remain free from seed and soil borne diseases, insect-pests and other disorders and show enhanced tolerance to adverse climatic conditions like low and high temperature, rainfall, hail etc. Plants show increased resistance against insect-pests and diseases throughout their growth period.

Preparation method: About 20 l water is taken in a plastic tub in which 5 kg dung of *desi* cow, 5 litres urine of *desi* cow, 250 g burnt lime, and 100 g virgin soil (collected from around the tree) are slowly added. The solution is stirred for 2-3 minutes with a wooden stick in clockwise direction. The solution is covered with jute bag and kept overnight. Next day, the solution is stirred for 2-3 minutes in clockwise direction. The prepared *Beejamrit* solution is used for treating planting material within 2 days and left over solution is discarded thereafter.

The seeds or planting material are treated before sowing with 200 ml *Beejamrit* per kg seed. The seeds of selected crop are spread on a tarpaulin sheet and *Beejamrit* is sprinkled on it so as to enable its wetting. In case of vegetative propagating crops, tubers/ rhizomes/sets/grafts of selected crop are placed in a bamboo basket and the basket is dipped in a tub containing *Beejamrit* for 15-20 seconds for treatment. The seeds are dried in shade and used for sowing the next day.

2.*Darekastra*: This solution is used to manage sucking insect-pests and young caterpillars attacking fruits and vegetables.

Preparation Method: The branches of *Darek* tree are cut in small parts.About 40 litres water, 2 litres cow urine, 400 g cow dung and 2 kg chopped branches are put in a barrel.The solution is stirred for 2-3 minutes in clockwise direction so that all the contents get mixed well.The solution is stirred intermittently for 2 days in clockwise direction for 2-3 minutes and then covered with jute bag. It takes 2 to 14 days for *Darekastra* to get ready. The solution is strained through a cloth and stored in a barrel/drum away from direct sunlight and rainfall and can be used for upto 6 months.

Application Rate: 500 litres/ha (undiluted)

***3. Brahmastra*:** This solution is used to control sucking insect-pests and older larvae infesting crops.

Method of preparation: About 200 g crushed and ground leaves of any five plants (*Darek*, sugar apple, castor, papaya, mango, guava, thorn-apple, *Duranta*) are taken in a big vessel to which 4 litres cow urine is added and it is covered with a lid. The solution is boiled on low flame and then kept aside for cooling for 48 hours. The solution is stored in a container away from direct sunlight and rainfall and may be used upto 6 months.

Application Rate: Add 12.5 litres *Brahmastra* is in 500 litres water for spraying in 1hevtare area.

***4. Agneyastra*:** This solution is used against pests like fruit borers, root borers and leaf folders that are hidden inside fruits, roots and leaves of plants.

Method of preparation: About 10 litres cow urine, 5 kg crushed and ground leaves of *Darek*, 500 g each of tobacco powder, chilli powder and crushed garlic are put in a vessel. The solution is heated on low flame till it starts boiling, removed from it and cooled for 48 hours. The solution is strained through cotton cloth and stored in a cool place. It can be used for upto 6 months.

Application Rate: Mix 12.5 litres *Agneyastra* in 500 litres water for spraying in 1 hectare area.
5. *Dashparni*: This solution is used to control all types of insect-pests infesting crops, fruits and vegetables.

Method of preparation: In a barrel having 40 litres water, about 4 litres urine of *desi* cow, 400 g dung of *desi* cow, 100 g turmeric powder, 100 g Ginger paste, 500 g Asafoetida (*heeng*) powder and 200 g tobacco powder are put and then covered with a jute bag. Next morning, 200 g green chilli powder, 100 g garlic (*desi*) paste, and 400 g *Darek* leaves are added. The contents are mixed with a wooden stick for 2-3 minutes in clockwise direction and covered with jute bag for 24 hours. Next day, 400 g each of leaves of any 10 plants viz. castor (chopped), *Dhatura*, papaya, marigold, mango, guava, *Arjuna*, *Bana*, *Basuti*, turmeric, ginger leaves and golden shower are added in the mixture and covered with jute bag. The mixture is stirred for 2-3 minutes every morning and evening for 30-40 days in clockwise direction.

Application Rate: Mix 12.5 litres *Dashparni* in 500 litres of water for spraying in 1 hectare area.

***6. Neemastra*:** It is used to control sucking insect-pests and young caterpillars attacking various crops.

Preparation Method: About 5 kg neem leaves/fruits are crushed and ground into fine powder and put in a drum to which 100 litres water and 5 litres of cow urine is poured and after that 1 kg cow dung is added in it. The mixture is stirred with a wooden stick in clockwise direction and covered for 48 hours. The solution is stirred thrice for 2 days and strained through a cloth and used for spraying.

Application Rate: Mix 25 litres strained solution in 250 litres of water for spraying in 1hectare area Natural formulations for managing insect-pests on various crops are summerised in Table 17.1 .

Table 17.1: Natural formulations for managing insect-pests on crops

S. no.	Formulation	Insect-pests against which effective
1	*Beejamrit*	Soil insects
2	*Darekastra & Neemastra*	Sucking pests, mealy bugs and young caterpillars
3	*Brahmastra*	Sucking pests, pod borers and fruit borers but does not control internal borers
4	*Agneyastra*	Sucking pests, pod/fruit borers and internal borers
5	*Dashparni*	Sucking pests, internal borers and difficult to control pests

Few investigations on insect-pest and nematode management under natural farming

- Chilli-garlic extract (5%) applied twice a week under protected cultivation could effectively manage aphids, grasshoppers and crickets in tomato, cucumber and capsicum.
- *Brahmastra* and *Darekastra* used alternatively @10% at weekly intervals successfully managed the sucking pests of okra viz. leafhoppers and aphids under natural farming.
- *Dashparni* extract (5 %) was reported to cause 5.44, 13.52 and 16.52 per cent mortality of *Myzus persicae after* 24,48 and 72 hours of spray in capsicum (Sharma, 2014a) whereas, *Agneyastra* (5%) was moderately effective in reducing population of aphids, *Lipaphis erysimi* on mustard.
- Sharma (2014b) reported that in peas, *Agneyastra* 5 per cent resulted in the lowest number of mined leaves per plant by leaf miner, *Chromatomyia horticola* i.e. 122.07 and 62.87 as compared to control viz. 248.93 and 103.49 during 2013 and 2014, respectively and the least percentage of infested leaves/ plant and least number of leaf miner maggots.
- Thakur and Sood (2019 and 2022) revealed that *Darekastra* and *Tamarlassi* @ 10% exhibited moderate level of acaricidal activity against red spider mites infesting cucumber in polyhouse. Natural products, used as preventive management measures, resulted in low level of mite infestation and higher net returns and *Darekastra* registered the maximum net returns.
- Anees (2018) reported that Neem Baan 1500 ppm resulted in the highest reduction (48.94%) in larval population of *Spodoptera litura* on tomato followed by NSKE (36%), *Darekastra* (19.05%)*,Panchgavya* (14.10%) *Agneyastra* (12.90%), *Dashparni* (10.30%) *and* cow urine (10%) on tomato crop after 3 days of spray All the products exhibited repellent, feeding deterrent and ovicidal activities against third instar larvae of *S.litura.*
- Among the various organic inputs, *Agneyastra* (5%), *Brahmastra* (5%) and cow urine (10%) were found effective against brinjal shoot and fruit borer (*Leucinodes orbonalis)* recording lower shoot and fruit infestation as preventive as well as curative sprays (Sood, 2018).
- Weekly sprays of *Darekastra* (5%) + *Agneyastra* (5%) were effective in reducing the larval population of *Spodoptera litura* on tomato in polyhouse (Badiyala and Kanwar, 2020). In capsicum, *Spodopera* larval population could be kept under check by daily handpicking the larvae in naturally ventilated polyhouse, spraying *Neemastra* 10% and green larvicide and installing pheromone traps in polyhouse @ 2 traps/250 m^2.
- *Neemastra* @ 20% registered significantly least (2.15 and 2.40 hoppers $leaf^{-1}$) population of *Empoasca flavescens in* castor and it was at par with the other organics including insecticidal

check (2.63 leaf^{1}) but was superior to untreated control (3.8 leaf^{1}) (Kumar and Sarada 2020).

- Minimum Root knot nematode infestation was recorded in *Agneystra* @ 800 ml/10l water followed by in *Neemastra* @ 400 l /acre and in *Brahmastra* @ 800 ml/10l when applied as drenching near root zone area of the tomato plants at the time of transplanting and repeated after 15, 30 and 45 days after transplanting as compared with all other treatments (Maru et al. 2021).

III. Natural Products for Disease Management
1. *Beejamrit*: As discussed under section II

2. Fermented butter milk (FBM): It is used to protect plants against fungi, bacteria and viruses. This solution contains growth hormones which increase resistance in plants against the diseases.

Preparation Method: The butter milk, prepared from milk of *desi* cow, is placed in sunlight and allowed to ferment. This process may take 4-6 days in summers and upto 10 days in winters. As soon as the froth starts appearing on the butter milk, it is ready for use and 3 litres of fermented butter milk is added in 100 litres water and stirred well with a wooden stick in clockwise direction for 2-3 minutes and FBM is ready to use.

3. **Dry *Kandi***
Preparation Method: Five to seven days old cow dung (about 3 kg) is taken and grinded to /broken into fine powder with the help of a wooden stick and the powder is is collected in a thin cloth preferably musclin cloth to make a bundle (*potli*). This bundle is tied with a long rope and the other end of the rope, having potli, is tied in the centre of a 3-4 feet long stick.One hundred litres of water is taken in a drum and the *potli* is hung on a wooden stick in such a way that it dips in water and it is kept suspended in water for 48 hours. It should be protected from rain water. The water in the drum will start to turn copper coloured after 48 hours or more. The *potli* is then taken out and squeezed, again dipped and squeezed. This process is repeated for three times and the entire extract of the *potli* will be squeezed and past in the drum. This solution is stirred with a wooden stick and used within 48 hours for spraying.

4. *Saunthastra*
Preparation Method: One hundred gram of s*aunth* powder is taken in a container having one litre of water. It is stirred well with a wooden stick to suspend the powder completely in water.The solution is boiled on low flame till its quantity reduces to half and allowed to cool. One litre milk of *desi* cow is boiled in another container and 5 ml each of boiled milk and the *saunth* solution are put in 100 litres water in a drum. The solution is slowly mixed with a wooden stick so that all the contents are dissolved properly. The drum is kept covered with jute bag for 2 hours and strained through a cloth and used within 48 hours.

5. *Rambaan*
Preparation Method: Eight litres of *jeevamrit* and 3 litres fermented butter milk are taken in a drum and the water is added to make the final solution 100 litres. The solution is mixed properly with a wooden stick and strained through a cloth and used within 48 hours.

Preventive sprays of aony of the above prepared solutions can be done with the appearance of any disease and may be repeated after 7-10 days for 2 months depending upon its severity

6. Plant paste/slurry: It is useful against various diseases on fruit crops.

Preparation Method: Fifty litres of water is taken in a drum to which 20 litres of cow urine and 20 kg of cow dung is added to which 10 kg paste of *Darek* or any other bitter leaves is added followed by addition of 200g turmeric and 10g asafoetida powder. The contents are stirred well with a wooden stick and covered with a jute bag for 48 hours. The plant paste/slurry is ready to use.

It is applied 4 times in a year i.e. in 2nd to 3rd week of May, last week of September to first week of October, between 21st December and 14th January, and between Holi and onset of spring season.

Few investigations on disease management under natural farming

- Fermented butter milk sprays @10% were effective in managing leaf spot in tomato crop under protected condition.
- Reddy et al. (2006) reported that fresh buttermilk was significantly superior to fermented butter milk in reducing the spread of urd bean leaf crinkle virus on urd bean (*Vigna mungo)*. FBM increased the incubation period of the virus in the plant.
- Ashlesha and Paul (2014) found that drenching and spraying with *Panchgavya* (5%) + fermented cow urine (5%) exhibited maximum control of soil borne (*Fusarium* wilt, stem rot and root rot) and foliar diseases (*Phytophthora* blight and anthracnose) in capsicum.
- The formulation of plant growth promoting rhizobacteria, *Bacillus amyloliquefaciens* prepared in butter milk reduced the incidence of tobacco streak virus on cotton (Vinodkumar et al., 2018).
- The collar rot disease of tomato was effectively managed by three sprays of *Tamarlassi* (@ 10%) and fermented butter milk (10%) sprayed at weekly intervals under protected conditions (Badiyala et al. 2022).

Conclusion and way forward

Natural farming, being eco-friendly and sustainable can be instrumental in addressing the issues of poor agricultural production, and thus poor returns to the farmer. It will reduce gap between agricultural and non- agricultural sector, agricultural debts and expenses of costly imported inputs i.e. fertilizers, pesticides etc. amongst the small and marginal farming community. Adoption of natural farming can replenish soil health by mulching, application of *Jeevamrit/ Ghanjeevamrit*, proper aeration and using farm produced inputs for managing insect-pests and diseases. It will result in reduction of labour and production costs. Natural farming will facilitate production of chemical free food and save the people from many health-related concerns. In addition, soil fertility can be enhanced by increase in the biodiversity of soil micro/macroflora and available nutrients. Inter/ multiple-cropping is encouraged which will result in more income.

Nevertheless, the studies being in preliminary stage require multilocational evaluation and validation by unbiased, autonomous bodies like ICAR to determine the impacts of indigenous products on soil, land and environment health. The long-term impact and viability of the model needs to be scientifically validated before it can be scaled up and endorsed across the country. Also, its effects on socioeconomic status of farmers and food security of nation need to be investigated in depth.

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18. ROOT KNOT NEMATODES – A FORMIDABLE CHALLENGE TO CULTIVATION OF CROPS IN PROTECTED CULTIVATION

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Abstract: The ever-increasing human population, necessitates increased food production. Continuous availability of off-season crops and huge profitability has led to a paradigm shift in global crop production towards protected agriculture. However, this protected cultivation system is inflicted by soil borne pathogens especially plant parasitic nematodes among which root knot nematodes have emerged as a major constraint to the production of crops under protected structures posing a serious management challenge to the growers and scientists. Continuous cultivation of susceptible crops, conducive climatic conditions in terms of temperature and humidity, recycling of nematode-infected growing soils and planting materials are the major factors for their high infestation leading to tumerous growth in poly/ nethouses. The growers need to be made aware of these notorious pathogens, their cause, spread and management options for sustained production under PA. Phasing out of most of the effective nematicides, and direct consumption of vegetables require the need for adoption of a holistic approach for their management integrating preventive and curative measures to avoid proliferation of nematode pathogen populations. Integration of various practices viz. sanitation and sterilisation, maintenance of healthy soils, use of amendments and bioformulations/chemicals needs to be adopted for eco-friendly and sustainable management of nematode populations.

Introduction

Agriculture has undergone significant developments in its growing patterns from the primordial to the present times, so as to get better quality and quantity using available resources with new dimensions. Increased pressure of globalization and modernization has led to outdating of traditional agricultural practices and knowledge and adoption of modern agricultural practices with main focus on production, capital gain, input intensity and crop consistency. In the face of these new changes; vegetable and horticulture crops are fast emerging as major commercial ventures due to higher remunerations per unit area and high-tech production of these high-value horticultural crops under protected as well as in open conditions with the adoption of modern technologies to increase the yield. It provides benefits of producing off-season crops with export quality attributes, higher productivity with minimal use of chemicals and water resources. However, contrary to the expectations of protected cultivation, pests and diseases continue to be major problems. Amongst different soil borne pathogens nematodes have acquired a threatening proportion in poly/ nethouse protected cultivation of crops.

Nematodes are invertebrate round worms which are prevalent in almost all the habitats, but being microscopic in size, these are often overlooked. They are worm like multicellular microorganisms lacking skeletal, circulatory, respiratory and specialized organs for locomotion and respiration. These are the most abundant animals on the earth (van den Hoogen et al., 2019) forming a dominant component of the soil (Bardgett and Van Der Putten, 2014). The rhizosphere soil around the small plant roots and root hairs is a rich habitat for various kinds of nematodes. Soil-inhabiting nematodes can be classified according to their feeding habits viz., the free-living (microbivorous, saprophytic and predators) and plant parasitic nematodes. Free-living nematodes inhabit all types of soils and some of these play crucial role in organic matter recycling. The plant parasitic nematodes (PPNs) dominate in soils having vegetation. They may be ecto-parasitic (feeding on the root surface) or endoparasitic (feeding inside root). PPNs pose a great threat to agriculture causing an annual yield loss of over $100 billion globally (Abad et al., 2003; Thoden et al., 2011). Besides direct damage to crops, PPNs predispose the plants to other pathogens like fungi, bacteria etc. thus forming disease complexes. Soil borne diseases especially fungal and bacterial wilts become more damaging in the presence of root knot nematode. PPNs have been the cause of decreasing yield potentials, but have not received due attention as that of insects, fungi, bacteria and viruses because of their microscopic size, production of non-specific symptoms and mostly underground habitat. They have been often referred to as hidden enemies also. However, the changing climatic conditions and cropping patterns have favored buildup of nematode populations and these are gaining importance.

Among various plant parasitic nematodes, root knot nematodes belonging to genus *Meloidogyne* are the most destructive and are becoming constraints to production of crops because of their polyphagous nature, short life cycle and high fecundity rate. They are widespread all over the world (Jones et al., 2013), and their population in the soil increases easily under congenial conditions (Calderón-Urrea et al., 2016; Hajihassani et al., 2018).

Root-knot nematode: Host range, biology & life cycle

Root-knot nematodes are polyphagous pests and have been reported to attack more than 5500 plant species including vegetables (tomato, potato, okra, cucumber, eggplant, cucurbits, carrot, lettuce *etc*.), pulses, fruits, fibre, cereal, plantation and ornamental crops (Trudgill and Blok 2001). Several weed species (226 species belonging to 43 families) are known to act as hosts of root knot nematodes the worldwide (Rich *et al* 2008). *Meloidogyne incognita* is known to infest and reproduce on >138 weed hosts also. The host range of root knot nematode is very wide and it is hard to find any non- host plant (Olsen 2000). Most of the crops being grown under protected cultivation including tomato, capsicum, cucumber, brinjal and carnation etc., are highly prone to nematode attack (Cheema *et al.* 2004). The extent of damage caused is directly related to the population densities of nematode.

The life cycle of *Meloidogyne* consists of four juvenile stages (J_1-J_4) and it is completed in 25 to 30 days depending upon the host and environment (Fig. 18.1). Temperature plays an important role in development and multiplication of the nematode, and the temperature range of 25-30^{o}C is highly congenial. Under conducive environmental conditions, nematode population build-up increases rapidly. The reproduction is mostly parthenogenic, female remain attached to the feeding site and on maturity lays about 600 eggs which are bound together by a gelatinous matrix. This gelatinous matrix protects eggs from unfavourable conditions and helps in survival of the nematode in the soil in the absence of suitable host. Hatching of eggs is mostly spontaneous and the first moult takes place inside the egg itself. The second juvenile stage (J) is infective. It hatches from the eggs and invade the host at the elongation zone of roots and migrates through the cortex towards the root tip and induces the formation of large multinucleate cells called "giant cells" to form galls (Koltai and Bird 2000). Juveniles J_3 and J_4 do not feed as they lack stylet. The energy requirements of nematodes are fulfilled before the start of second moult for the completion of further moults. The stylet regenerates during the final moult and the adult female resumes feeding. Completion of the life cycle of root knot nematode depends upon the successful induction and maintenance of these specialized feeding sites.

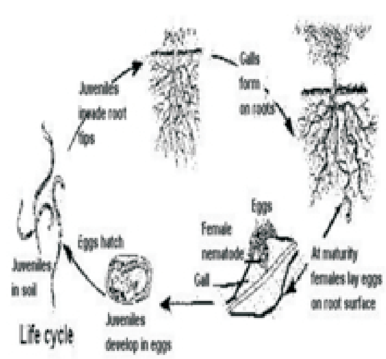

Fig 18.1. Life cycle of root knot nematode (source: http://eagri.org/eagri50/PATH172/lec07)

Symptoms

Root knot nematode causes two type of symptoms i.e., above and below ground symptoms. The above ground symptoms include chlorosis of leaves, stunting and wilting of plants and are generally confused with nutrient deficiency symptoms. The disease generally occurs in patches. The most characteristic symptoms are the below ground symptoms, which include formation of galls on the roots. The size and the shape of galls depend on the species of root knot nematode, the level of infection and the host plant. On highly infested plants the galls on the roots tend to fuse together to form multiple galling. The nematodes attack the roots of the host plant and establish its feeding site on vascular parenchyma resulting in formation of 'giant cells' by hypertrophy and hyperplasia of parenchyma cells (Fig. 18.2). The formation of giant cells results in swollen roots called root-knots or root galls which damages the water and nutrient-conducting abilities of the roots. It leads to the manifestation of above ground symptoms on plants in patches such as yellowing, wilting, poor fruiting etc. These patches (Fig. 18.3) gradually increase every year with the increase in inoculum. Galled roots are more prone to be attacked by other soil-borne, disease-causing microorganisms (Agrios 2005).

Factors responsible for multiplication of root-knot nematode under protected cultivation:

Controlled environmental conditions in protected cultivation having high temperature and humidity increases the attack of pathogens including plant parasitic nematodes especially the root knot nematodes (Sharma *et al* 2009). In net/ polyhouses there is continuous availability of moisture around root zones through drip irrigation which is responsible for fast build up of nematode and movement as compared to the open field where both the flooded and dry conditions prevail. Temperature is very important factor for nematode multiplication and temperature range of 25-30°C is the most favourable for their survival and reproduction. Under net/ polyhouses, prevailing temperature conditions are congenial both for the crop and for nematodes. The root knot nematodes, due to their short life cycle (25-30 days), are able to complete a greater number of generations (Hajihassani et al., 2018). Moreover, most of the crops grown under net/polyhouses (tomato, cucumber, capsicum, brinjal, ornamentals etc.) are susceptible to root knot nematodes. Intensive monoculture of susceptible crops leads to nematode build-up and their higher multiplication rate. All these factors i.e. favourable environment, susceptible host and monoculturing crops on the same piece of land favour the fast build-up of nematode population in protected structures and once nematodes are introduced, it is very difficult to get rid of these nematodes.

Spread of root knot nematode in the soil:

Root knot nematodes rarely move more than a few inches in a thin film of water at their own in the soil. Indirectly, these can disperse with infected transplants and infested soil. Inside the net/polyhouses, these are spread by implements used for cultural operations. Irrigation or drainage water and infected seedlings are the major source of their spread. Minute galls formed on tender roots (Fig. 18.5) harbour the female of root knot nematode and inadvertent transplanting of these galled or knotted roots lead to completion of life cycle resulting in multiplication of the nematode in the soil. They start feeding on the host plants, their population increases tremendously and it becomes cumbersome to manage these nematodes.

Management of root knot nematodes under protected cultivation:

The management of root knot nematodes becomes pertinent for sustainability of the protected cultivation system. Various options including cultural, biological, physical, use of host resistance, and chemical measures are being practiced for their management. But it is very difficult to manage them using single management option. Cultural control measures are commonly used, however because of the broad host range of *Meloidogyne* spp. and presence of mixed populations of different nematode species (Xiang et al., 2018) it is not practically feasible. Use of host resistance has been an effective and economical management strategy for root knot nematodes, but commercially resistant cultivars are not available in every crop (Xiang et al., 2018; Hajihassani et al., 2019).

Recently, several chemicals e.g., methyl bromide and aldicarb have been withdrawn from the market due to environmental and human health concerns and toxicity to non-target organisms (Kim et al., 2018; Xiang et al., 2018) and new products continue to become commercially available and are being evaluated for root knot nematode management. The integrated nematode management strategies including soil solarization, biological control, organic amendments, crop rotation, field sanitation, and limited use of chemicals have been explored. Management of root knot nematodes in protected cultivation may be considered under two heads i.e. (a) preventive measures and, (b) curative measures.

a) Preventive measures

Preventive measures involve precautions which help to avoid the entry of pest into the healthy areas. These include;

- Site selection for the construction of new polyhouse is very important. Fields grown with cereal crops viz., rice or wheat should be preferred. Low lying areas should be avoided so as to avoid flooding of polyhouse during rainy season which may lead to entry of water borne nematodes into the polyhouse from the adjoining fields.
- Use nematode free transplanting material. Soil-less media should be used in clean and sterilized plastic trays for raising seedlings which should not come in contact with infected soil.
- All the machinery and tools should be cleaned and disinfected before entery and use in the protected structures.
- Use clean irrigation water and its flow should not be from nematode infested field to the healthy field and prefer drip irrigation system.
- Crop debris should be removed along with roots after the termination of crop so as to decrease the inoculum load to the succeeding crop. Infested crop roots, harbour the nematode larvae and eggs and sanitation can minimize the problem
- There should be a provision of foot pond with potassium permaganate solution inside the door enclosure of the net/polyhouse for sterilization of shoes/slippers of visitors and farm labour before entering the protected structure.
- Destroy weeds in and around the structure for managing the diseases and proper crop growth. Many weeds are host of different pathogens and help them to survive in the absence of host.

b) Curative measures

Curative measures of nematode management include control measures like cultural, biological, chemical, and host resistance etc., that are adopted to reduce nematode population below economic threshold levels.

i) Soil solarization: Soil solarization is the most effective means to reduce the nematode population in hot weather areas (temperature around 40-50^{o}C). North Indian conditions are the best to adopt this practice to reduce nematode infestation under polyhouses. Transparent polyethylene mulch (25 µm thick LLDP) is used to cover the moist soil for 4–8 weeks in the month of May–June (Katan, 2017). Greenhouse effects can be created under transparent polyethylene sheet leading to higher temperature which is lethal to nematodes.

ii) Green manuring/ use of antagonistic crops: Green manuring with sunhemp and *Dhaincha* helps to replenish the soils. Green manuring with 50 days old sunhemp and 60 days old marigold decreases the nematode population, while green manuring with *Dhaincha* increases root knot nematode abundance. Thus, *dhaincha* incorporation should be avoided in nematode infested soils (Recommendations given by PAU)

iii) Resistant cultivars and grafting technique: Growing of resistant cultivars (if available) is one of the most economical and convenient options against plant parasitic nematodes. Grafting of commercially desired susceptible cultivars on resistant rootstock is becoming popular in vegetable crops under protected conditions. ICAR- IIVR Varanasi has developed grafting technology to reduce the problem of root knot nematode in vegetable crops.

Figure 18.2 Root knots or galls on mature roots of cucumber (a); tomato (b); capsicum (c); and brinjal (d) plants

Figure18.3 Root knot nematode infested capsicum crop in a polyhouse

Figure 18.4 Healthy capsicum crop

Figure 18.5 Root-knot on nursery plants of tomato

Solanum torvum, wild brinjal germplasm, has been identified resistant against root knot nematode and was used as root stock to graft with scions of promising tomato varieties cv. Kashi Aman, Kashi Vishesh and Hissar Lalit. Grafted plants showed desirable resistance against root knot nematode by reducing soil population, reproduction and gall index. Resistant rootstock of wild relatives of brinjal viz., *S. toxicarium*, *S. sisymbriifolium* and *S. torvum* have been grafted with commercial tomatoes and noticeable reduction in galling was recorder (Black et al. 2003). Grafted rootstock of melon and capsicum showed promising results to minimize root galling in the greenhouses (Kokalis-Burelle and Rosskopf 2011).

iv) **Organic amendments:** Enormous organic amendments are used for suppression of plant parasitic nematodes in protected cultivation. Suppression efficacy of organic amendments depend on their concentration and active ingredient. Non-edible oil cakes of neem (*Azadirachta indica*), castor (*Ricinus communis*), karanj (*Pongamia glabra*), mahua (*Madhucala tifolia*) etc. are used for management of root-knot nematode in protected cultivation (Patil et al 2021). Organic materials viz., FYM, vermicompost, slurry, green manure etc. are also effective for suppression of PPNs.
Soil amendments with mustard cake and neem cake @ 1 t/ha along with FYM @ 2.5t/ha ten days before sowing of cucumber is recommended by PAU, Ludhiana. It helps to reduce root knot nematode infestation in roots of cucumber and improves the soil health.

v) **Biological control: U**se of biological control agents is becoming popular due to their environmental friendly nature and targeted results. Among various bioagents, egg parasitic fungus *Paecilomyces lilacinus*, *Pochonia clamydosporia*, antagonistic fungus *Trichoderma viride*, *T. harzianum*, VAM fungus *Glomus* spp., bacterial parasite *Pasteuria penetrans* and PGPR bacteria *Pseudomonas fluorescence* are used as potential bio-agents against plant parasitic nematodes. Bio-agents enriched organic amendments exhibit increased efficacy to control nematodes in protected cultivation.

Chemical nematicides: Use of chemical nematicides is not much encouraged in vegetable crops due to their residual effects. However, to manage very high nematode populations, some new chemicals like flunosulfone and flupyram are being evaluated. The growers depend on integrated pest management practices for nematode management under polyhouse and the integration of all possible preventive and curative measures should be practiced to control nematodes under polyhouses as an effective strategy.

Conclusion:

Growing of crops under protected cultivation system is of paramount importance in present agricultural scenario of India. Due to the burgeoning human population, arable land is decreasing day by day and to meet the ever-increasing demand for the supply of vegetables, protected cultivation is the best option. However, nematode problem is gradually increasing under protected cultivation due to favourable environment and intensive and mono cropping. Proper monitoring the soil population build up and adoption of preventive measures and intelligent and judicious integration of the best possible management options can help to manage the nematodes and sustain the protected cultivation system.

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19. DYNAMICS OF AGRICULTURAL PESTS AND DISEASES IN THE WARMING CLIMATE

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Abstract: The exact impacts of global warming are still not very clear however; it is widely accepted that it would greatly affect the agricultural pattern and the associated insect pests and diseases. The effects of climate change on insects are complex, as it some insects inhibit others through the impact on their distribution, diversity, abundance, development, growth and phenology. Uncertainties regarding different aspects of climate change such as small-scale variability in increase of temperature and atmospheric CO_2, changing precipitation patterns, relative humidity and other factors further add to the uncertainties for the future infestation of insect pests and diseases and their spread. There is enormous heterogeneity of insect species and their host plants and global climate variability. Hence, mixed responses of insect species to global warming are expected in different parts of the world. However, it is generally expected that there will be an overall increase in the number of pest outbreaks involving a broader range of insect pests, pathogens and the vectors would expand their geographic distribution towards the higher latitudes and higher altitudes. Invasive pest species will establish more readily in new areas and there could be more insect-transmitted plant diseases; and effectiveness of natural enemies could reduce significantly. Favourable conditions for pest infestation and crop damage due to climate change factors pose a signi?cantly high risk to already challenged human food security. Therefore, there is a great need for formulating adaptation and mitigation strategies in the form of modi?ed IPM practices, climate and pest monitoring, and the use of modelling tools.

Introduction

Insect pests and diseases have been causing huge damages to agriculture since the beginning of organised cultivation. Pests and diseases affect agricultural production by adversely affecting the plant health and growing population, diverting nutrients from the produce or by destroying the marketable product. Climate is an important determinant of the occurrence, severity, abundance and distribution of agricultural pests, pathogens and vectors. The spatial and temporal severity varies depending on weather conditions during or prior to the crop season. Climate affects the insects, mites, nematodes, other invertebrates, vertebrates and microbial pests and vectors. Climate is an important factor for controlling the probable damage being caused through their reproduction, development, survival, spread, abundance, distribution, by altering host defences and susceptibility. Indirectly, climate also manifests its impacts through altering the interactions between the pests and other species such as their natural enemies, competitors, vectors and mutualists.

Sir Boris Urarov, the famous Entomologist and locust specialist, in his classic paper on “Insects and climate” indicated that “*The climate of every area on the surface of the earth has undergone a long series of great changes throughout geological history. Patterns of glacial advances and retreats, changes in sea levels, changes in rainfall patterns etc. have had their effects on earlier civilizations, but the difference in the changing climatic patterns in recent years have been augmented at the unusually fast rate, thanks to the anthropogenic environmental changes, mostly degradation or destruction of the world's natural habitats, as well as the combined effects of habitat loss, fragmentation, pollution and climatic changes which have posed a severe threat to World's biodiversity”* (Urarov, B.V. 1931).

Insect pests, pathogens, crop hosts and the environment:

The study of plant pests/disease initiates with the discussion of the “plant disease triangle” (Fig. 19. 1a). The three arms of the triangle – host, pathogen, and environment – must be present and interact appropriately for the infestation/disease to occur. The disease triangle is a fundamental principle illustrating the factors involved in the occurrence and severity of plant disease. Disease caused by a living agent requires the interaction of a susceptible host, a virulent pathogen, and a favourable environment. Plant disease is prevented when any one of these three components are eliminated or modified. Some plant pathologists have expanded the usefulness of the disease triangle concept by adding one or more factors such as "time", "human activity" or "vectors" to represent special-case applications which can be represented by one of the vertices of a three-dimensional pyramid-called disease prism (Fig. 19.1b).

Temperature*:* Temperature is the most important weather variable in insect pest and pathogen development. The correlation generally follows an asymmetric curve ranging between a cold and a hot lethal threshold, with an optimum temperature in between (Figure 19.2). The minimum and maximum temperature extremes determine the potential geographical range and species distribution, in addition to influencing population dynamics.

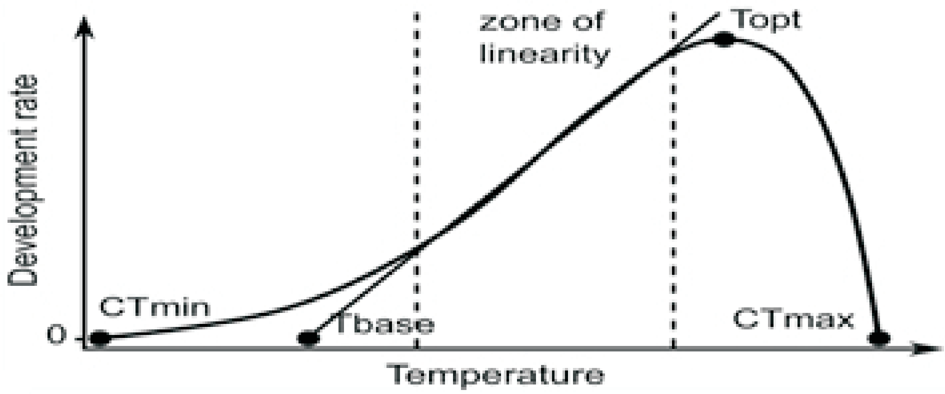

Fig. 19.2. Theoretical relationship between temperature and development rate of insects or pathogens (CTmin, CTmax, Topt and Tbase are the critical thermal minimum, maximum, optimum, and base temperatures, respectively).

Humidity*:* Humidity affects both the host plants and the pest/pathogen in various ways. Effect of humidity is similar to that of temperature with lower, upper and optimum values for pest and pathogen development. The effects however, are highly contextual with some pathogens such as apple scab, late blight, and several vegetable root pathogens are more likely to infect plants with the increased moisture whereas, pathogens like powdery mildews tend to thrive under relatively lower moisture. Incidence of some fungal pathogens are known to be favoured by longer periods of high humidity.

Rainfall*:* There are few studies on the effect of precipitation on insects. Heavy rains tend to remove or kill some insects, vectors and pathogens. Flooding seems to be a controlling factor for some insects and pathogens overwintering in soil. Flooding of soil due to heavier precipitation is known to control some insects/spores overwintering in soil. A combination of temperature and precipitation affects insect pests, predators, parasites, and diseases resulting in a complex dynamic. Overall impacts, however, are not linear as the changes and interactions between different weather parameters can impact insect pest, predators, parasites, pathogens the plant growth, development and resistance resulting in complex dynamic and non-linear interactions. Rao et al. (2004) reported that varying combinations of weather parameters show varying effects on the incidence of *Helicoverpa armigera* in cotton crop.

3. Global Warming:

Global warming has become one of the most concerning issues in various spheres of human activities in the light of its projected adverse impacts on different socio-economic sectors including agriculture and horticulture. The vulnerability of agriculture to the changing insect pests/pathogens due to rising temperatures and associated changes in precipitation patterns & increasing climatic extremes has become one of the most vulnerable issues in the global economic, social, scientific and political forums.

3.1 Global Climate Change:

The Intergovernmental Panel on Climate Change (IPCC), in its 6th assessment report (AR6) has concluded that human activity induced increased concentration of Green House Gases (GHGs) has resulted in consistent increase in global mean temperature by ~1.2^{O}C since, the pre-industrial times (Fig. 19.3). Each of the last four decades were successively warmer than any decade that preceded it since 1850. Global surface temperature in first two decades of the 21st century (2001-2020) was 0.99°C higher than that of 1850-1900. Global surface temperature was 1.09°C higher in 2011–2020. Globally mean precipitation over land has increased since 1950, with a faster rate of increase since the 1980s. It is *likely* that human influence contributed to the pattern of observed precipitation changes since the mid-20thcentury (IPCC, 2021).

3.2 Climate Change over India:

According to Krishnan et al., (2020), a significant warming trend was observed in all India mean annual surface air temperature for the long-term period i.e. 1901–2010 based on the estimates derived from the India Meteorological Department (IMD) gridded monthly station data. The annual mean temperature over India has increased from the mid-twentieth century (Fig. 19.4), with an increased rate of 1.5 °C per 100 years between 1986 and 2015. The warming is not uniform across the seasons, with considerably more warming in the pre-monsoon season (March–May) than in other seasons. Analysis by the India Meteorological Department of Time series and trend in mean temperature anomalies during the period 1901-2021 showed that the annual mean temperature for different seasons viz. Winter (January to February), Pre-Monsoon (March to May), Monsoon (June to September) and Post-Monsoon (October to December) have increased at the rates of 0.63, 0.70, 0.57, 0.43 and 0.90 °C per 100 years, respectively (IMD, 2022).

The all-India monsoon seasonal rainfall series however, does not show any significant trend. It displayed multi-decadal variations in which there was a clustering of wet or dry anomalies. The time series evolution of anomalies, expressed as percent departures from its long-term mean (Fig. 19.5) showed alternating periods extending to 3-4 decades with less and more frequent weak monsoons over India, indicating a cyclic nature of the monsoon. An important finding about the monsoon season rains has been that the incidence of heavier rainfall are increasing whereas, the incidence of reduced rainfall has been decreasing (Goswami et al. 2006) indicating that the contribution from increasing heavy rain events has been offset by decreasing light/moderate rain events (Fig. 19.6).

The precipitation trends over the hilly regions in India are different from those in other parts of the country whereas, trends in precipitation over western Himalayas showed ranges at different altitudes (Singh et al., 2011; Jaswal et al., 2014; Jaswal et al., 2015; Shekhar et al., 2017). The study on climatic trends revealed decreasing trends of rainfall and increase in maximum and minimum temperatures in mountain state of Himachal Pradesh (Rana et al., 2012). Snow precipitation has also been decreasing in the Himalayas. Bhan and Singh (2011) reported that solid precipitation (snowfall) over Shimla for all the winter months registered a decreasing tendency with decreasing contribution of snowfall to total winter precipitation and shrinking of snowfall season. No significant change was observed in the beginning of snowfall season however, it is terminating earlier at a rate of about 12 days per decade. Changing rainfall pattern has also caused changes in water balance in different basins. Rana et al. (2014) reported that low hill regions of Himachal Pradesh (India) exhibited water surplus during kharif season and water deficit during rabi season whereas, the mid hill regions exhibited water deficit during kharif season and water surplus during rabi season during past three decades. The farmers' perceptions pertain to climate change in Himachal Pradesh also substantiated change in climatic parameters and concluded that climate variability has a clear impact on crop productivity in climate dependent agricultural systems. (Rana et al. 2013).

4. Global Warming and Climate Change - Future Scenario:

4.1. The Global Scenario:

According to the IPCC AR6 (IPCC, 2021), increase in average global temperature will be determined by the amount of greenhouse gas emissions over the next several decades. The development of many countries is dependent on fossil fuels as the main source of energy hence, greenhouse gases will certainly be released.

IPCC has speculated and discussed five possible scenarios called the Shared Socioeconomic Pathways (SSPs) which are the projected socioeconomic global changes up to 2100 and are used to derive greenhouse gas emissions scenarios.

A brief description of these scenarios and most likely change in global temperatures associated with each of these are briefly described below.

SSP1**:** It is labelled as SSP1-1 and it is the most optimistic scenario wherein the global CO_2 emissions are cut to net-zero by 2050. The temperature rise of 1.2-1.7, 1.2-2.0, and 1-1.8 ^{O}C by the year 2024, 2040, and 2100, respectively is predicted under this scenario

SSP2**:** It is labelled as SSP1-2.6, and this scenario assumes that global CO_2 emissions are cut severely, but not as fast as required. It would reach net-zero after 2050. The temperature rise predicted under this scenario is 1.2-1.8, 1.3-2.2, and 1.3-2.4 ^{O}C by 2040, 2060, and 2100, respectively.

SSP3**:** It is labelled as SSP 2-4.5, IPCC calls it 'middle of the road' scenario under which the CO_2 emissions are the same as the current levels before starting to fall around mid-century but do not reach net-zero by 2100. It is predicted that a temperature rise of 1.2-1.8, 1.6-2.5, and 2.1-3.5 ^{O}C is expected by 2040, 2060, and 2100, respectively.

SSP4**:** It is labelled as SSP3-7.0. The CO_2 emissions in this scenario rise steadily, doubling the emissions from the current levels by 2100. The temperature rise predicted under this scenario is 1.2-1.8, 1.7-2.6 and 2.8-4.6 ^{O}C by 2040 and 2060, and 2100, respectively.

SSP5**:**It is labelled as SSP5-8.5. IPCC warns the world to avoid it at all costs. It is assumed that imagine the current CO_2 emission levels to approximately double by 2050. As the global economy grows significantly, it is fuelled by exploiting fossil fuels and energy-intensive lifestyles. The temperature rise predicted under this scenario is 1.3-1.9, 1.9-3.0 and 3.3-5.7 ^{O}C by 2040 and 2060, and 2100, respectively.

Range of global temperature changes till the year 2100 under different SSPs are depicted in Fig.19. 7. According to IPCC (2021), these changes will not be distributed equally across the globe. Higher latitudes and mountainous regions are expected to get a larger share of this warming and the precipitation is also projected to increase over high latitudes, the equatorial Pacific and parts of the monsoon regions. However, these will decrease over parts of the subtropics and in limited areas of tropics. Heavy precipitation and hot weather days are also expected to increase under various climate change scenarios throughout the world and extreme daily rain events are projected to intensify by about 7 per cent for each one degree Celsius of global warming.

4.2 The Indian Scenario:

According to Krishnan et al., (2020) projections by climate models of the future scenario in India are based on multiple standardized forcing scenarios called Representative Concentration Pathways (RCPs). Each scenario is a time series of emissions and concentrations of the full suite of GHGs, aerosols, and chemically active gases, as well as LULC changes through the twenty-first century, characterized by the resulting Radiative Forcing *(A measure of an imbalance in the Earth's energy budget owing to natural (e.g., volcanic eruptions) or human-induced (e.g., GHG from fossil fuel combustion changes)* in the year 2100. The two most commonly analysed scenarios were “RCP 4.5” (an intermediate stabilization pathway that results in a Radiative Forcing of 4.5 W/m^2 in 2100) and “RCP 8.5” (a high concentration pathway resulting in a Radiative Forcing of 8.5 W/m^2 in 2100). The projected changes (Fig. 19.8) suggested that as compared to base line period of recent past (mean of 1976–2005), mean increase in various parameters are projected by the year 2100 by the end of the twenty-first century. The temperature is projected to be by ~2.4 and 4.4°C under the RCP 4.5 and RCP 8.5 scenarios, respectively and warming is expected to be higher over the Himalayan region. Under RCP 8.5 scenario, temperatures of the warmest day and the coldest night of the year are projected to rise by approximately 4.7 and 5.5°C, respectively whereas, frequencies of occurrence of warm days and nights are projected to increase by 55 and 70%, respectively and frequency of summer (April–June) heat waves are projected to be 3 to 4 times higher and mean duration of heat wave events is projected to approximately double (Krishnan et al., 2020).

The models projected an increase in the mean and variability of monsoon precipitation with continued

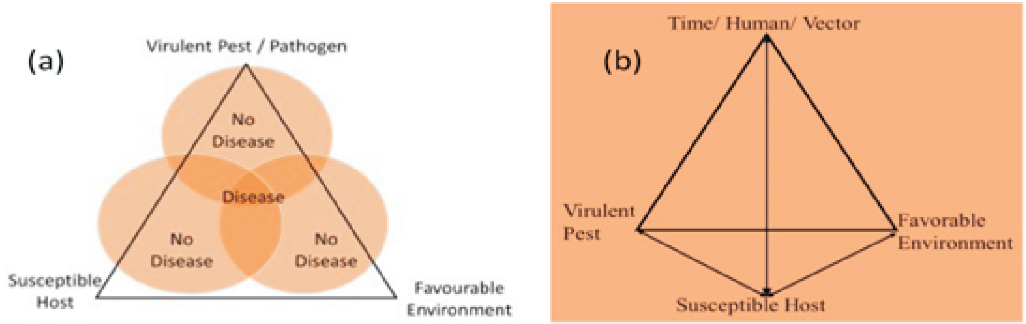

Figure 19.1 Disease Triangle (a) and Disease Prism (b)

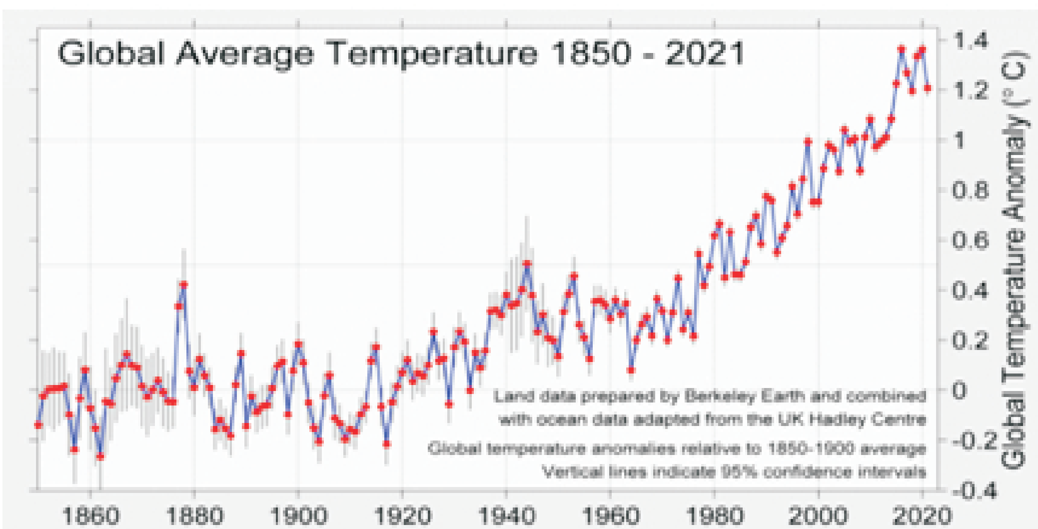

Figure 19.3 Global mean temperature anomaly from 1850-2020 average (Courtesy: http://berkeleyearth.org/global-temperature-report-for-2021/)

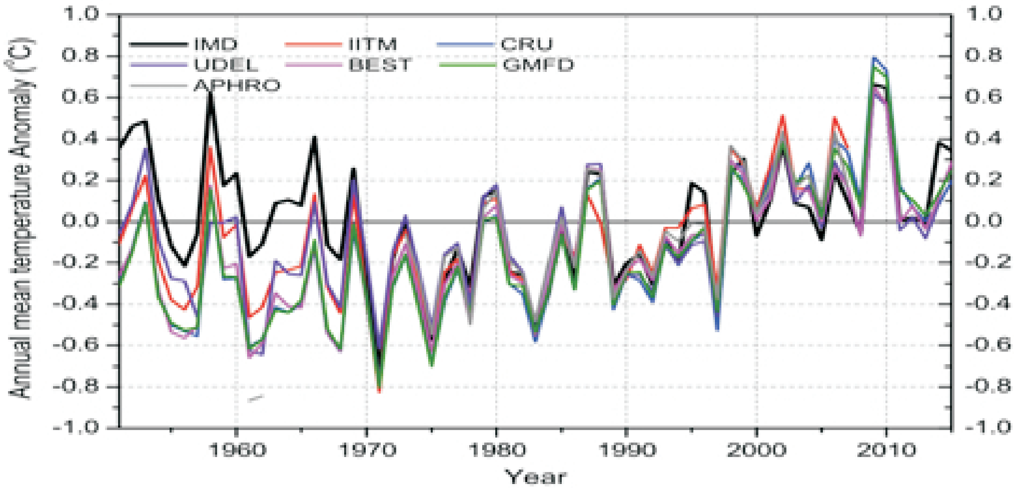

Figure 19.4 Indian annual average land surface air temperature anomalies relative to 1981–2010 climatology in the observed datasets (IMD: India Meteorological Department; IITM: Indian Institute of Tropical Meteorology; CRU: Climate Research Unit; UDEL: University of Delaware; BEST: Berkeley Earth; GMFD: Global Meteorological Forcing Dataset; APHRO: Asian Precipitation—Highly Resolved Observational Data Integration Towards Evaluation)

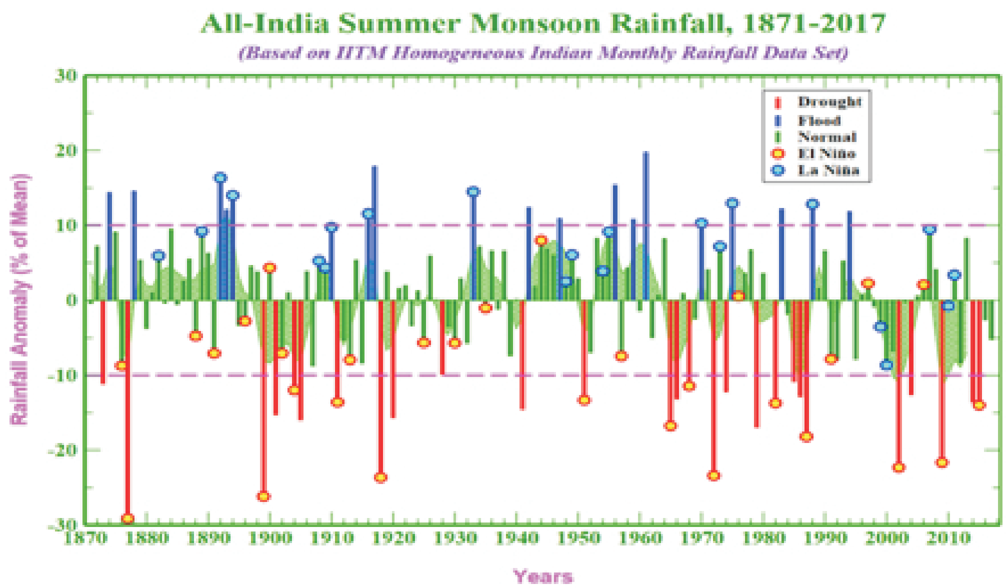

Figure 19.5 Anomalies of All-India Monsoon Rainfall expressed as percent departures from its long-term mean

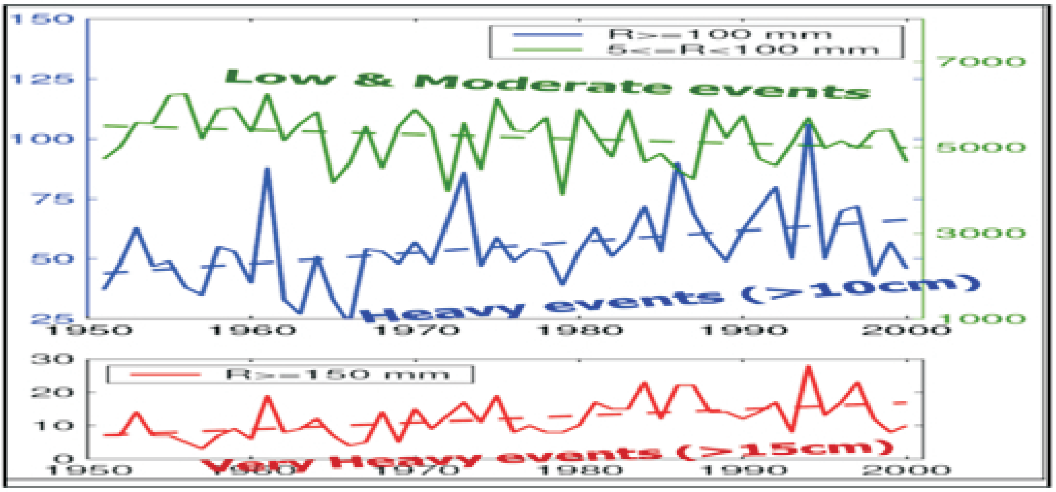

Figure 19.6 Temporal variation (1951 to 2000) in the number of heavy (R ≥ 100 mm/day), moderate (5 ≤R < 100 mm/day) and very heavy events (R ≥150 mm/day) daily rain events during the summer monsoon season over Central India.

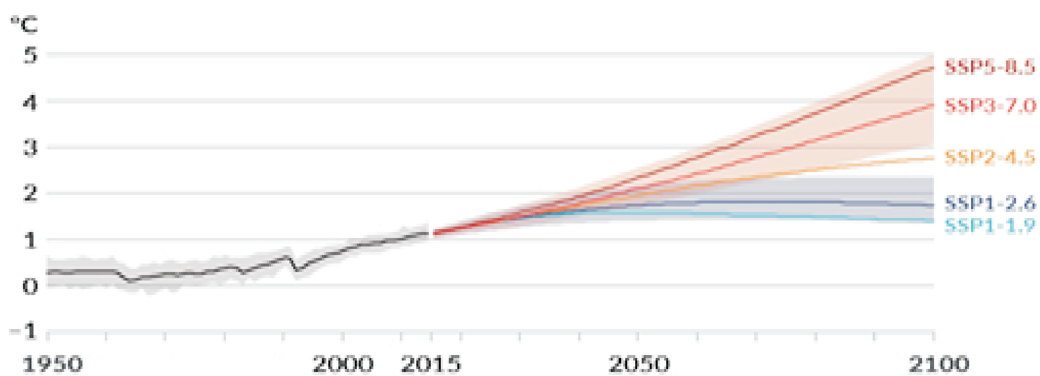

Figure 19.7 Global temperature changes (^{o}C) relative to 1850-1900 under different SSPs

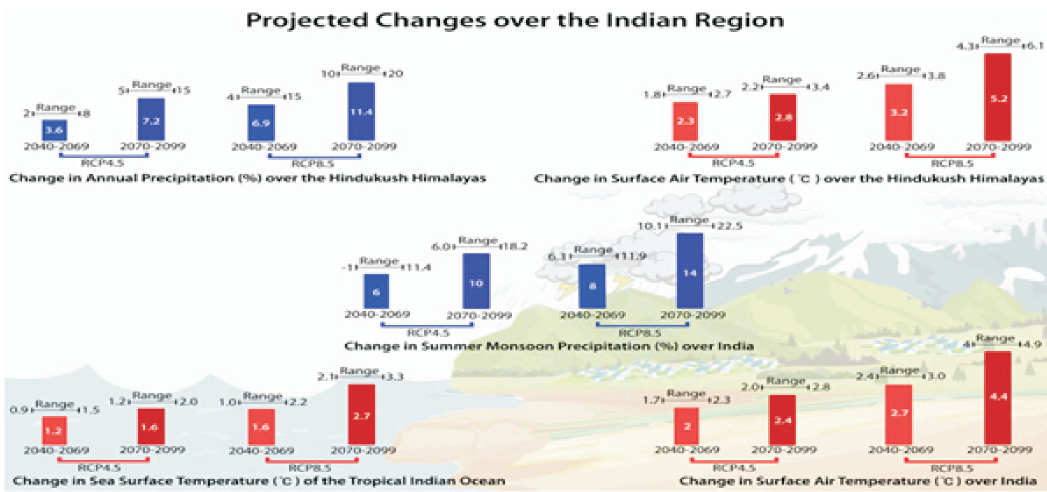

Figure 19.8 Best estimate and range in climate model projections of future changes i.e. in 1. Surface air temperature over India (°C; bottom right panel), 2.Sea surface temperature of the tropical Indian Ocean (°C; bottom left panel), 3.Surface air temperature over the Hindu Kush Himalayas (°C; top right panel), 4.Summer monsoon precipitation over India (% change; centre panel), 5.Annual precipitation over the Hindu Kush Himalayas (% change; top left panel). All the changes are computed relative to their climatological average over the 30-year period 1976–2005 (Krishnan et al., 2020).

global warming by the end of the twenty-first century, together with substantial increases in daily precipitation extremes. Mukherjee et al. (2017) have reported that the frequency of extreme precipitation showed an increasing trend prominent over southern India.

5. Effects of climate change on insect pests and pathogens:

The major predicted results of climate change i.e. increase in temperature, moisture & CO_2; and change in rainfall pattern can impact all the three arms of the plant disease triangle in various ways. However, it is difficult to precisely predict the impact of climate change on plant diseases.

Climate change will affect the plant pest/disease dynamics in intricate ways. Effects of changes in temperature and humidity on pests are reflected through winter survival, increased fertility, accelerated population development, increased growth and virulence, reduced dormancy, and wider geographical range. The host may be affected through increase/decrease in stress leading to increase/decrease in susceptibility and through coincidence/avoidance of susceptible phases. The host ecosystem will also be influenced through changes in effectiveness of vectors & natural predators; and imbalance of development synchronicity. It may also affect distribution and introductions of new pests. These impacts, will certainly be subjected to increased human interventions through change of production period, modified pesticide applications, breeding of pest resistant varieties including genetically modified cultivars, introduction of natural enemies, shifting of crop production ranges and increased trade of host commodities.

5.1 Direct impacts of change in weather variables:

Impact of temperature: Impacts of rising temperature are manifested through:

- i) Reproduction, development, survival and consequent increased number of generations of the pests and pathogens;
- ii) Survival, overwintering and dispersal;
- iii) Expansion of geographic area;
- iv) Outbreak of diseases transmitted by insects;
- v) Modified relationships/ synchrony of the pests and their hosts, environment, and other species such as natural enemies, competitors and vectors.

Temperate climate zones with mean cold temperatures may experience longer periods of temperatures suitable for pathogen growth and reproduction under the warming climates. Coakley et al. (1999) have shown that wheat and oats become more prone to rust diseases with increased temperature whereas; some forage species become more resistant to fungal disaeses with increased temperature. Earlier initiation of warm temperatures could lead to an earlier threat from the pests and diseases with potential for more severe infestations. "Migratory" insects may arrive earlier in their host areas; or the area of their overwintering may be expanded. Enhanced temperature could impact insect pest populations in several complex ways. Some climatic changes in temperature may depress insect populations however, the warmer temperatures in temperate climates will lead to more diverse insects with higher populations. Trends in increase of temperature in extra tropics and hilly areas may lead to optimal temperatures for growth and development of many insect pest species, potentially reducing thermal constraints on population dynamics leading to increased pest infestations under global warming scenarios. However, in areas of tropical regions where, the temperatures may exceed the thermal tolerance limits, pest abundance and infestation may reduce in some cases. Lehmann et al. (2020) reported mixed responses to climate warming in different insect pest species indicating that temperature rise leads to increased pest severity in most of their studies. However, 59% of all species analysed showed responses that could reduce their harmful impact, mostly via reduced physiological performance and range contraction.

Effect of rainfall and humidity: Distribution and frequency of rainfall may affect the incidence of pests directly and through changes in humidity levels. Under climate change, frequency of rainfall would decline, while its intensity would increase. Under such situation, incidence of small pests such as aphids, jassids, whiteflies, mites etc. may be reduce as these get killed or washed away by heavy rains. Chander (1998) reported that aphid population on wheat and other crops was adversely affected by rainfall and sprinkler irrigation. Flooding of soil due to intense rains may limit some insects, particularly those overwintering in the soil. Fungal pathogens of insects are favoured by high humidity and their incidence would increase by climate changes that lengthen the periods of high humidity and would be reduced by the changes of drier conditions. Increased inter-spell durations due to changing climate may lead to water deficiency for crops. Plants stressed by drought become more susceptible to insect attack due to decrease in the production of secondary metabolites with defence function (Yihdego et al., 2019). Timing of rainfall has also been reported to be have affect on insect pest infestation in crops. Higher rainfall and moderate temperatures during vegetative and early reproductive stages lead to rapid multiplication and increased infestation of American bollworm in cotton (Bhan and Kharbanda, 2004).

Impact of CO_2 changes: Generally, CO_2 impacts the insects indirectly i.e. resulting from changes in the host crop.

5.2 Other impacts of climate change:

***Expansion of habitat range*:** Insect pests and pathogens are cold-blooded, and temperature is the most important environmental factor influencing their distribution, development, survival, reproduction and infestation potential. Distribution of pest population is expected to expand into regions that might become favourable as a result of global warming. Climate projections indicated that majority of insect species will extend in the higher altitudes and latitudes. Parry and Carter (1989) predicted that $1^{O}C$ increase in temperature would extend distribution of species in northern hemisphere i.e. 200 km towards north or 140 m upwards. However, there could be species/region specific variations in terms of timing, population size, and habitat ranges for drawing most likely scenarios. Lopez-Vaamonde et al. (2010) reported that 97 non-native Lepidoptera species belonging to 20 families established in Europe, and 88 European Lepidoptera species in 25 families have expanded their habitat range in Europe, with 74% of species becoming established in the last century. Parmesan et al. (1999) reported that in a sample of 35 non-migratory European butterflies, 63% have shifted their ranges to the north by 35–240 km, and only 3% had shifted to the south in 20th century. It has also been reported that some pests and pathogens may withdraw from regions that become unfavourable due to increased uncongenial summer temperatures.

Changes in over-wintering and migrating behaviour: With delayed beginning of winters, onset of hibernation may be delayed and may be suspended earlier than the usual in spring thereby increasing the activity period of pests. The pests can, therefore, colonize crops more quickly during spring. Increase in temperature will also enable the insect pests and vectors to over-winter at higher latitudes prompting a change in the migration behaviour. Early spring emergence, particularly in temperate regions, has been recorded for many species (Roy and Sparks, 2000; Gordo and Sanz, 2006; Hassal et al., 2007; Van Asch et al., 2007). The studies for tropical regions are limited. The relationship, in extra tropics and other cold regions, is complex as individuals within post-diapause are primed to initiate development as soon as favourable conditions are experienced. Upon the resumption of development, many of the stress-tolerance mechanisms are 'switched off', and the stress-tolerance of a phenotype is significantly reduced (Hayward et al., 2005). Any post-diapause cold spell may adversely impact the pest population. Birthal et al. (2021) reported that the changing climate would lead to shift in cropping pattern in different parts of the country and such shifts may have impacts on crop pests and diseases also.

***Loss of synchrony with environment*:** Synchrony in phenology between an insect and its environment is crucial to maximise the individuals' fitness. Loss of synchrony could have significant impact on community dynamics at the ecosystem level. Parmesan (2007) reported altering of many plant–insect herbivore interactions by the warming climate, the 'starting point' prior to climate change might not be the 'perfect synchrony' in all the cases hence, climate change may not always lead to 'diminished synchrony' between insects and their host. Huang and Hao (2020) have reported that climate change induced asynchronous changes between phenology of wheat & cotton crops, and *Helicoverpa armigera* has been leading to increased infestation.

Changes in inter-species interactions: The effect of climate change on distribution, abundance and infestation potential involve direct effect on each species individually and on the interspecific interactions. Differential response of species in the food chain to climate change could result in decoupling of the synchronized dynamics between insect pests and their natural enemies impacting the abundance, distribution, and seasonal timing of natural enemies. Hance et al. (2007) reported that if a natural enemy starts to develop at a slightly lower temperature and develops faster than the prey, a too early and warm spring leads to its early emergence and there is high probability of its death due to lack of prey.

Changes in population growth rates: Warming would affect annual and multi-voltine species in different ways and extents. In multivoltine species, higher temperatures would allow faster development rate thus allowing for additional generations within a year (Pollard and Yates, 1993). It has been observed that tropical insects are relatively sensitive to temperature changes and are currently living very close to their optimum temperature (Deutsch et al., 2008). This implies that with 2-3^{O}C rise in temperature the ambient temperature may exceed the upper limit of favourable temperature range, thereby adversely affecting growth and development of pests.

Indirect effect through host plants**:** Higher levels of CO_2 induce growth and increased plant size and canopy density with more conducive microclimate for the pests. Increase in C:N ratio of plant foliage increases feeding of herbivores to derive more amino acids. Fuhrer (2003) reported that increased atmospheric CO_2 can affect the distribution, abundance, and performance of herbivorous insects. CO_2 increase can affect consumption rates, growth rates, fecundity, and population densities of insect pests. The effects of increasing CO_2 levels on insect pests are highly dependent on their host plants, (Lincoln et al., 1984). C3 plants may be positively affected by elevated CO_2 and negatively affected by insect response whereas, C4 plants are less responsive to elevated CO_2 and therefore, less likely to be affected by changes in insect feeding behaviour. Rao et al. (2014) observed a higher relative proportion of carbon to nitrogen (C: N) in peanut foliage grown under elevated CO_2 and reported that the pest incidence was likely to be higher in the future. Elevated CO_2 had a positive effect on BPH multiplication that resulted in more than double of its population compared to ambient CO_2.

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20. IDENTIFICATION OF NUTRIENT STRESS IN CROPS GROWN UNDER PROTECTED ENVIRONMENT

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Abstract: Plant stress detection is considered as one of the most critical areas for the improvement of crop yield in the compelling worldwide scenario. Several abiotic and biotic stresses affect plant growth, yield and quality of crops harvested for human or animal nutrition, textile etc. In addition to water and sunlight, plants require adequate amount of nutrients for proper growth and vitality. Generally, macronutrients are acquired in larger amounts as compared to micronutrients as they are the part of the basic components in plant cell and tissue development. Shortfall of any nutrient, particularly nitrogen, phosphorus and potassium results in different stress-induced responses *viz.*, early defoliation of leaves, restricted root or shoot growth and decreased biomass yield. Nutrient stress in greenhouse crops can be more severe due to the limited rooting volume and limited nutrient reserve to the crop plants. Therefore, identification of nutrient stresses using different approaches is becoming need of the hour to their proper and timely redressal and to ensure sustainable yields under protected environment.

Introduction

Global food security is being threatened by the rapid increase in population and drastic changes in the climate (Lesk et al., 2016). In the wake of changing climate, plant stresses *viz.,* abiotic and biotic have become the most important limiting factors for the crop productivity and ultimately to the food and nutritional security. Moreover, the present critical food security situation has been exacerbated by the restrictions of movement and trade due to the recent Covid-19 crisis. Subjected to biotic and abiotic stressful conditions, crop plants respond through physiological and metabolic changes mediated by pulses of gene expression, suggesting the existence of a complex signalling network that allows the plants to recognize adverse environmental conditions as well as changes in growth conditions (Kollist et al., 2019). It is pertinent that under protected conditions, nutrients are usually supplied with water in a precise manner to enhance quality production per unit area per unit time (Choudhary et al., 2012). Crop plants grown under natural conditions in the field or protected cultivation are inflicted by varied stresses. Among predominately occurring stresses, nutrient stress imposes significant shortfalls in the yield of crops. Nutrient stress is a complex phenomenon, understanding of which requires the co-ordinated efforts of soil scientists, agronomists, ecologists, physiologists, biochemists and molecular biologists. Nutrient stress may result from either low levels of available nutrient element or its presence of excess concentration in plants. In some cases, the presence of one element in excessive concentration may induce the deficiency of another element. Therefore, it becomes extremely urgent to define novel technologies and methods to identify nutrient stress to ensure better growth and yields of all crops.

Visual deficiency/toxicity symptoms, in field evaluation techniques (rapid tissue tests, plant analysis in labs, chlorophyll meters and leaf colour chart) and machine vision technology constitute various evaluation techniques for nutrient stress in crop plants under protected environment. In this context, attempt has been made to show the availability, functional aspects, and deficiency/toxicity symptoms of 14 elements essential for the survival of plants and others which produce phytotoxicity. Visual analysis provides a valuable basis for assessing the nutritional status of the plant. Deficiency symptoms are the consequence of metabolic disturbances at various stages of plant growth. Nutrient deficiency symptoms in plants vary from species to species and element to element. In general, the deficiency symptoms comprise yellowing of leaves, darker than normal green colour, interveinal chlorosis, necrosis, twisting of leaves, etc. The toxicity symptoms may be due to a specific toxicity of the metal to the crop or due to an antagonism with other nutrients. The most general toxicity symptoms are stunted plant growth and chlorosis of leaves. The use of rapid tissue tests of plant saps is also common in field evaluation diagnostic technique. Plant analysis on the other hand is also an important diagnostic tool in assessing the composition of plants and in monitoring the nutrient levels. Moreover, an early warning system of nutrient stress (i.e., before symptoms are visible in the plant) would indeed be the best tool that helps the growers to detect stress of particular nutrient. Recent development in the machine vision technology has special advantage in terms of providing valuable scientific insights to assess nutrient stress in crop plants.

Visual deficiency/toxicity symptoms

Chemical analysis of plants may indicate the presence of more than 90 elements but 17 of them are essential for successful growth and development of plants. Any imbalance among these nutrients leads to emergence of nutritional disorders owing to deficiencies or toxicities. Visual deficiency symptoms are generally characteristic enough to permit for easy detection of deficiency of a nutrient as these appear on particular plant part at specific growth stages. The location of the symptoms of nutrient deficiency on plants depends on the extent and rate of nutrient mobility from older to new leaves. Toxicity symptoms vary depending on the nutrient element and the crop. Excessive quantities of other nutrients in the soil may cause nutrient imbalance in crop plants resulting in poor crop quality. Listed below are the important deficiency and toxicity symptoms in crop plants under protected environment:

1. Nitrogen:

Deficiency- Leaves turn pale green to yellow from tip towards base, frequently a V-shaped yellowing and browning of leaves can be seen. Oldest leaves are affected first due to high mobility of nitrogen through phloem, but in severe cases whole plant becomes chlorotic. Growth of plant is usually stunted.

Toxicity- Excess nitrogen, in general, induces green vegetative growth and may delay flowering. Plant foliage may be dark bluish-green and new growth is succulent. Plants are easily subjected to disease and insect infestation and to drought stress. The plant becomes prone to lodging, blossom abortion and lack of fruit set occurs. Generally, higher levels of NO_3 inhibit root growth and leads to decrease in the root: shoot ratio (Scheible et al. 1997; Zhang et al., 1999).

2. Phosphorus:

Deficiency- Leaves appear reddish-purple. Green portion of leaves may become grey green with purple stem base. The oldest leaves are affected first. Plant growth is stunted and tillering gets reduced. Severe deficiency causes yellowish red leaves starting from the lower mature leaves from tip towards base.

Toxicity- Excess of phosphorus mainly induces micronutrient deficiency by inhibiting iron, zinc and copper uptake/translocation possibly due to precipitation of phosphates.

3. Potassium:

Deficiency- Leaves appear faded out and develop chlorosis followed by appearance of necrotic areas at the tip and along the margins. The oldest leaves are affected first due to high mobility of potassium in plants and show characteristic scorching around the leaf margins and margins of affected leaves may roll upwards. Stalks of the plant become susceptible for lodging.

Toxicity- Excess of potassium induces nitrogen and magnesium deficiency. This will stunt the growth of plant and lead to chlorosis.

4. Calcium:

Deficiency- The deficiency symptoms first appear in the growing tips and young leaves because of low mobility of calcium through phloem. Calcium deficiency induces premature shedding of fruit and buds. The tips and young leaves become chlorotic followed by necrosis of leaf margins. It leads to blossom end rots of many crops like tomato and capsicum.

Toxicity- Excess calcium in the growth medium interferes with magnesium absorption. High calcium usually causes alkaline pH which in turn precipitates many of the micronutrients making them unavailable to plants.

5. Magnesium:

Deficiency- Magnesium is mobile through phloem. The deficiency symptoms first appear in the older leaves and proceeds to young leaves. Magnesium deficient leaves show advanced interveinal chlorosis, with necrosis in highly chlorotic tissues. Older leaves may become reddish-purple while the tips and margins become necrotic. In its advanced form, magnesium deficiency may superficially resemble potassium deficiency.

Toxicity- Magnesium toxicity is not common. However, under drought like conditions, magnesium content usually increase in the leaves. Appearance of small necrotic spots can also be observed in older leaves. If the toxicity is more, the young leaves may exhibit spotted appearance.

6. Sulphur:

Deficiency- Sulphur deficiency first appears on the top. Young leaves turn light yellow often followed by pronounced yellowing from tip towards base and all the leaves on the plant become light yellow to yellow. The plants show restricted growth and the stem become thin and woody. The deficiency symptoms may occur either in young leaves in the presence of sufficient nitrogen or in old leaves in the presence of low nitrogen (Robson and Pitman, 1983).

Toxicity- Toxicity of sulphur generally reduces leaf size and overall growth of plants resulting in their stunting. Yellowing and scorching of leaves at their edges can also be seen in severe toxic levels.

7. Iron:

Deficiency- Deficiency symptoms first appear on young leaves showing interveinal chlorosis. Young leaves may be totally devoid of chlorophyll and the veins remain green. With passage of time the affected leaves become papery white, necrotic and ultimately die. In some crops, reddish spots may also develop.

Toxicity- Toxic levels of iron may cause bronzing, stunted top and root growth of the crops. High levels of iron may induce manganese deficiency in some crops.

8. Manganese:

Deficiency- Deficiency symptoms appear on young leaves as small chlorotic spots in the interveinal area of the basal part of the leaves and later extend towards the tip. Small necrotic spots develop on the leaves with yellow stripes and the veins remain green.

Toxicity- Generally, manganese toxicity shows chlorosis in young leaves. This may be due to Mn^{2+} induced iron deficiency since Fe^{2+} deficiency also shows chlorosis in young leaves. In many plants, the toxicity symptoms occur as interveinal chlorosis and necrosis. These symptoms are associated with deformation of young leaves and commonly known as "crinkle leaf".

9. Zinc:

Deficiency- Deficiency symptoms first appear on the second and third leaves from top of the plant. Leaves become thick and stalks will be shortened. The most important symptoms of zinc deficiency include rosetting i.e., stunted growth due to shortening of internodes, little leaf i.e., decrease in size of leaves and die-back i.e., death of shoot apices generally under severe deficiency of zinc.

Toxicity- Zinc toxicity induces stunted growth of crops, interveinal chlorosis in young leaves, which later on become dry and papery. Sometimes the affected leaves show the rolling of leaf margins and roots turn brownish and necrotic.

10. Copper:

Deficiency- Yellowing or dieback of youngest leaves is the characteristic symptom of copper deficiency. The leaf tips become white and leaves become narrow and twisted. In severe deficient conditions, plants show stunted growth.

Toxicity- Young leaves show interveinal chlorosis, while old leaves due to loss of turgor develop reddish orange or pink colouration and rolling of the leaf margins. In subsequent growth stages, leaves become dried and withered. Under severe toxicity, roots turn reddish brown and necrotic.

11. Molybdenum:

Deficiency- Under protected environment, molybdenum deficiency is very common and affects flowering and pollen producing capacity of crop plants. Visually symptoms are manifested as stunted growth and chlorosis in young leaves. Under severe deficient conditions, there is drastic reduction in leaf size and development of irregular leaf lamina in cauliflower commonly known as "whiptail" symptom. Older leaves exhibit necrosis of the chlorotic areas between the veins and leaf margins in molybdenum deficient plants.

Toxicity- Toxic levels of molybdenum induce golden yellow discolouration of the shoots along with malformation of the leaves. Reddish or golden yellow-coloured shoots can be seen under severe molybdenum toxicity in potato and tomato.

12. Boron:

Deficiency- Due to its immobility through phloem, boron deficiency symptoms first appear at the apical growing points or in young leaves. Young leaves become wrinkled and show darkish-blue green colour. Interveinal chlorosis may occur in mature leaves. The common boron deficiency symptoms are, "stem crack" in celery and "hollow stem" in cauliflower.

Toxicity- The toxicity symptoms usually appear in young leaves which develop chlorosis between the veins. The chlorotic areas become reddish brown and scorching of leaf margins can also be observed. In later stages, leaves become dry and papery. Flowering is also adversely affected by boron toxicity.

13. Nickel:

Deficiency- Plants suffering from nickel deficiency show interveinal chlorosis and necrosis initiating from the tip of the leaf. Nickel deficiency also results in delayed nodulation and reduced efficiency of nitrogen fixation in leguminous crops.

Toxicity- Distortion of young leaves, necrosis of leaf tips and margins and death of terminal shoot buds are the toxicity symptoms of nickel.

14. Chlorine:

Deficiency- Chlorine deficiency induces reduction in leaf area due to reduction in cell division, thus, lowers the dry matter production (Terry, 1977). Typical symptoms of chlorine deficiency are wilting of leaves, premature senescence of leaves and stem cracking. In tomato, leaves show chlorotic mottling, bronzing and tissue necrosis.

Toxicity- Burning of leaf tips or margins, bronzing, premature yellowing and abscission of leaves are the visual toxicity symptoms of chlorine.

In field-evaluation techniques

The use of rapid tissue test of plant saps is one of the common in-field diagnostic techniques for identifying nutrient stress. Plant tissue is tested for nutrient status to monitor the nutrient within the plants during the growing season and to diagnose a suspected nutritional deficiency or toxicity hence, this technique is a good management strategy in regulating nutrition under field conditions. The concentration of the nutrients in the cell sap is a good indication of how well the plant is supplied with the nutrients. These semi-quantitative tests are intended mainly for verifying or predicting deficiencies of nitrogen, phosphorus, potassium, sulphur and several micronutrients. The plant parts may be chopped up and extracted with reagents. The intensity of colour developed is compared with standards and used as a measure of nutrient concentration. Tissue tests are quick and easy to conduct and interpret. The time of sampling and plant part to be sampled for tissue tests have already been standardized for many crops and it can be done 5-6 times in a season and concentration can be monitored in the farm premises.

As in the tissue tests, a standardized method for time and method of sampling of plant parts are available for the laboratory based total plant analysis. The critical nutrient concentration is commonly used in interpreting plant analysis results and diagnosing nutritional problems (Fig. 20.1). Plant analysis depends on sampling the correct plant part at the appropriate growth stage (Table 20.1).

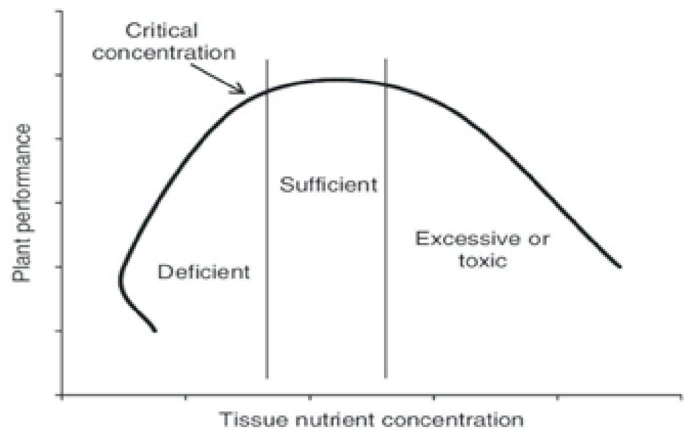

Fig. 20.1. Nutrient concentration in plant tissues as it relates to plant performance

Plant samples are collected on the basis of physiological age of the plant such as at pre bloom, mid growth or heading stage. It is not practically feasible to harvest and prepare entire plants for chemical analysis; therefore, a plant part such as leaf or petiole is used. However, it is essential that the plant part selected for chemical analysis accurately represents the nutritional status of the plant during its entire life cycle eg. in many vegetable crops, the most-recently-matured leaf (MRML) provides the most sensitive indicator of the nutritional status of the plant and sometimes only the petiole of this leaf is used for plant analysis. Different laboratory procedures have been developed for analysis of nutrient status in plants and is given in Table 20.2.

Recently, small hand-held spectrometers called chlorophyll meters are being used for testing nitrogen in intact leaves of plants. Chlorophyll meters direct beam of light corresponding to the wavelength absorbed by the chlorophyll molecule in the leaves. The meter essentially measures leaf greenness which is the measure of chlorophyll content in leaves. Similarly, leaf colour charts have also been employed to estimate leaf colour. Both chlorophyll meter and leaf colour chart constitute an important advancement in identifying nitrogen stress in plants.

Table 20.1. Sampling procedure for some crops under protected environment

Crop	Growth stage	Plant part to sample	Number of plants to sample
Tomato	Prior to or during fruit set	Young plants: Leaves adjacent to second and third clusters. Older plants: Leaves from fourth to sixth clusters	20 – 25
Cabbage	Prior to heading	First mature leaves from centre of the whorl	10 – 20
Bean	Prior to or during initial flowering	All the aboveground portion or fully developed leaves at the top	20 – 30
Root crops (Carrots and Onions)	Prior to root or bulb enlargement	Centre matured leaves	20 – 30
Cucumber	Early stages of growth	Newest expanded leaf	15 – 20
Capsicum	Prior to flowering and mid - stage	Youngest mature leaf	15 – 20

Table 20.2. Laboratory methods for analysis of different plant nutrients

Plant nutrient	Method
N	Micro-Kjeldahl method (Jackson, 1973)
P	Colorometric method (Jackson, 1973)
K	Flame photometric method (Black, 1965)
Ca and Mg	Atomic absorption spectrophotometric method (Piper, 1966)
S	Colorometric method (Johnson and Nishita, 1952)
Cu, Fe, Mn, Zn	Atomic absorption spectrophotometric method (Kalra, 1998)

Machine vision technology

Machine vision technology have been widely used in agricultural sector, such as precision agriculture, land and air-based remote sensing for the assessment of natural resources, quality detection and safety of post-harvest products, automatic processes and classification and sorting. This is because the machine vision system not only distinguishes the shape, size, texture and colour of the object but also provides its numerical attributes (Chen et al., 2002). Research on the detection of nutrient stress with image processing is still rare. Digital image processing is a part of this novel technology that deals with changes in digital images to perfect their features and characteristics. Operations on images are carried out using efficient algorithms specifically designed for image processing purposes. Input is the picture taken and the output is also an image that has been extracted. Image processing consists of 3 fundamental steps: Pre-processing, image segmentation and feature extraction (Fig. 20.2 & 20.3).

A. Pre-processing

Image capture is the first step in pre-processing. One can process the photos by using scanned images or data from digital cameras. The use of a scanner is effective to get 2D image such as for the identification of leaves (Tu et al., 2018). The farmers may take pictures on farms using a smartphone camera and send data to the nutrient deficiency/toxicity detection system automatically.

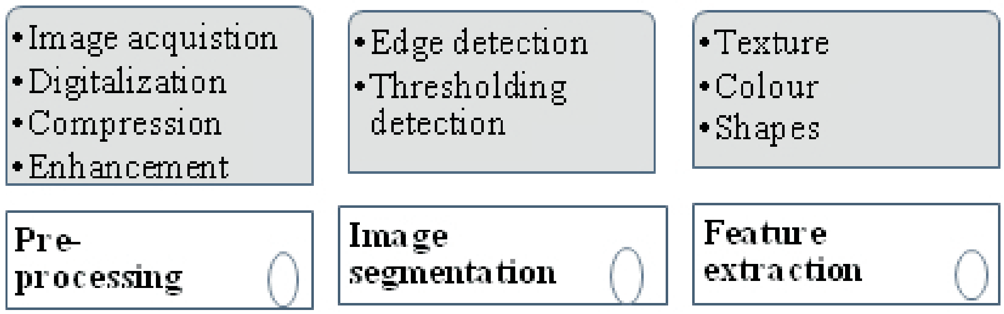

Fig. 20.2. Fundamental steps in image processing

A. Image segmentation

In image analysis, image segmentation is the first step after pre-processing. This step involves the partition of image into different attributes that are used for further analysis. The simplest way of segmentation is by using threshold detection system. The system can be classified based on range values set on the image pixel intensity value which generally involves conversion of input into binary segmented output images (Muthukrishnan and Radha, 2011). Edge detection system can also be used to find discontinuities in grey-level images. Problems due to noise and long processing times, however, make this detection system less efficient than threshold detection system.

B. Feature extraction

A feature is a number or a set of numbers derived from a digital image. Different techniques have been used to extract features from digital images. After the segmentation of the main image into various sub images containing region of interest, these features are used for detection of nutrients. Some of the commonly used methods are edge and boundary features, spatial features, transform features, colour features, shape features and texture features (Armi and Fekri-Ershad, 2019). Colour and texture are the best features for early detection of nutrient stress in leaves because what distinguishes less nutritious leaves from normal leaves lies in their colour, while what distinguishes the type of nutrients needed is seen in the texture of the leaves.

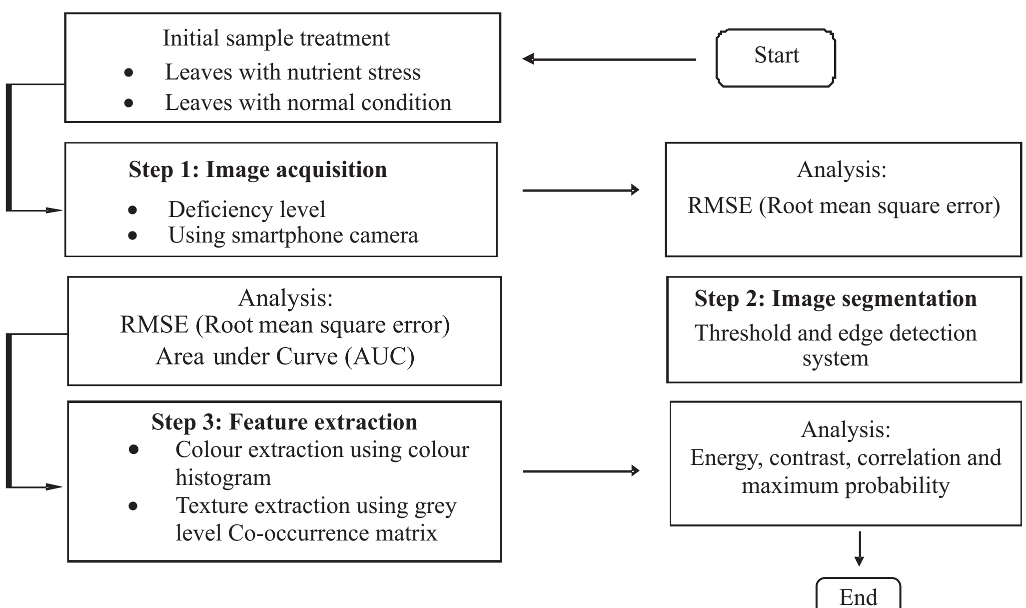

Fig. 20.3. Feature extraction

Conclusion

To address the severity of nutrient stress in crops under protected environment, it is vital to estimate the nutrient status of crop plants. The first level in identifying the nutrient status is based on visual deficiency or toxicity symptoms. Although, visual observation is subjective means of diagnosing the nutrient status but it is the cheapest and most rapid method. In many cases, estimation of plant nutrient status by means of rapid tissue tests and chemical analysis is required, either to confirm nutritional disorder or to exclude them if the symptoms do not point to a typical deficiency or toxicity of nutrient. Recent introduction of commercially available chlorophyll meters and leaf colour charts may also be deployed alongwith the use of traditional methods in assessing nutrient status of plants. Nevertheless, the recent and advanced machine vision technology is also gaining importance to identify nutrient stress in crops to face the current challenges in crop production under protected environment.

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21. PLANT NUTRIENT STRESS ASSESSMENT AND MANAGEMENT UNDER PROTECTED CULTIVATION

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Abstract: In the last two decades, India has seen a tremendous growth in area under protected cultivation. Protected cultivation practises are a cropping technique in which the micro-environment surrounding the plant body is governed partially or completely according to the requirements of the plants during their growth period to maximise yield and save resources. Under protected structures, soil must be viewed as a finite and non-renewable resource. Protected structures with their high output high input model exert tremendous pressure on soil often leading to its degradation. Development of salinity and nutrient deficiencies are of common occurrences over time. Specialised cropping pattern may adversely affect the soil's biological activity. The key to manage greenhouse nutrient issues requires its regular checking. The monitoring of quality of soil, therefore, forms an important aspect of nutrient management under protected structures. Frequent soil fertility evaluation helps to assess occurrence of any such problems and can help in checking the loss of soil fertility. Proper strategies need to be developed for sustaining soils under protected cultivation. This chapter deals with need for soil evaluation and various available techniques while putting forward a perspective for management of nutrient stress under protected structures.

Introduction

Even though agriculture has long been the mainstay of India's economy, our experience over the last 50 years has revealed a link between agricultural practises and economic well-being. The agricultural growth trend indicates a mix of notable accomplishments on the one hand, and missed opportunities on the other. In the present scenario, plant nutrient dynamics are highly influenced by global climate change and a string of extreme events (e.g., heat waves, droughts etc.). The availability of nutrients in the soil, their acquisition, assimilation, distribution/redistribution within plants, and nutrient budgeting can all be adversely disrupted by climate stress factors (Studer et al., 2017; Etienne et al., 2018). Such consequences may not be limited to the current growing season, but may also be applicable in future years. New and effective production technologies that can continuously improve the productivity, profitability, and respectability of the agricultural sector are required for self-sufficiency and food security of the poor in India, while the country should be to export high-quality fruits and vegetables.

Protected cultivation technology, though widely used in developed countries, but remained largely limited in India. However, in the last two decades, the country has seen an overall growth and presently approximately 50,000/2,15 lakh ha is under protected cultivation. The wide range of climatic conditions across the country's diverse topography allow for a wide range of cropping patterns. Huge crop losses are common in India due to climate extremes eg. floods, droughts, and other climatic anomalies, resulting in financial losses to the farmers. Concurrently, over the last decade, there has been an increase in demand for high-quality agricultural products. This has prompted the farming community to adopt region and crops specific protected cultivation technologies in India too.

Protected cultivation is an attempt to modify the natural conditions so as to achieve the maximum output. In protected cultivation cropping technique, the microenvironment surrounding the plant body is governed partially or completely according to the needs of the plants during their growth period to maximise yield and save resources. It's an attempt to manipulate natural conditions to maximise output. The techniques comprise a forced ventilated greenhouse, an insect resistant net house, naturally ventilated polyhouse, a plastic tunnel, a shade net house, raised beds, trellising and drip watering, etc.. Advantages of protective cultivation include:

- Protection of plants from biotic and abiotic stress
- Improvement in quality and quantity of produce

- Suitable for nursery raising as well as hardening of plant material
- Early maturity
- Round-the-year cultivation
- Reduction in use of pesticides through improved insect & disease management
- Efficient use of resources
- Production of genetically better transplants

Nutrient Stress Assessment

Intensive nature of protected cultivation result in huge pressure on the soil. There are numerous challenges associated with growing crops in protected cultivation, but in the present article nutrient stress management in protected cultivation structures has been focused. Nutrient management is a critical component of any crop production. Plant nutrition follows Liebig's "Law of the Minimum" (1855), which states that the "exploitation of the genetically ? xed yield potential of crops is limited by that nutrient, which is insufficiently supplied to the greatest extent" (Fig. 21.1) with all other growth parameters, eg. water availability and temperature, are assumed to be optimal in this theory. Plant nutrient status follows the normal Mitscherlich development functions, progressing from severe deficiency to moderate deficiency, optimum supply, and toxicity. Furthermore, a well-balanced nutrient supply is essential for protecting plants from all types of stress. Mastrodomenico et al., (2018) investigated the possibility of boosting performance under nitrogen stress using old maize varieties.

It's is fact that each crop's critical nutrient value varies depending on growth conditions, plant's developmental stage at the time of sampling, specific part of plant, determined nutrient species, the desired yield, and the mathematical approach used to calculate it. This infers that comparing results from different experiments is nearly impossible, as generally critical values are based on only one experiment. The literature shows enormous number of critical nutrient values for various crops, therefore, Smith and Loneragan, (1997) emphasised that for different nutritional levels, only ranges, not specific values, can be defined.

Assessment Techniques

The nutrient stress management becomes more important in protected structures as the selected crops/varieties have high yield potential, maximum production is realised from limited land, crop quality and growth rate are improved, nutrient requirements increase with continuous cultivation on the same soil and faster crop growth under warmer conditions. Hence, determination of nutrient availability becomes critical. Visual deficiency or toxicity symptoms, soil and plant analysis, and biological tests (Fig. 21.2) are among the various diagnostic techniques utilized for assessing potential nutritional related stress and the optimal quantity of nutrients required for desired plant growth. Further, this information is used to make fertiliser recommendations.

Unfortunately, the visual deficiency symptoms appear late in the season and by that time, reduction in yield potential has already occurred. Each of the techniques has its advantages and disadvantages and therefore, all the above-mentioned approaches should be integrated for an effective diagnosis of the problem and in turn improved management of nutrients.

Visual Assessment

One of most exciting and challenging attributes of nutrient management is being an effective soil fertility diagnostician. A plant's metabolism may be disrupted by nutrient deficiency, resulting in the production of many intermediate organic compounds in abundance and a shortage of others. The abnormal appearance of the growing plant is a visual method of evaluating soil fertility and diagnosing the disorder affecting the plant, as it can be a result of deficit of a particular nutrient. Chlorosis, necrosis, reddening, stunting, cessation of new growth, etc. are few of visual nutrient deficiency symptoms.

Visual deficiency symptoms are generally quite distinctive and allow for quick identification of nutrient deficiency appearing on specific plant parts at specific growth stages. Within a plant, the nutrients mobility varies greatly and nutrients such as N, P and K are quickly translocated from old to young leaves in stressed plants, and are considered as the mobile nutrients. They show their

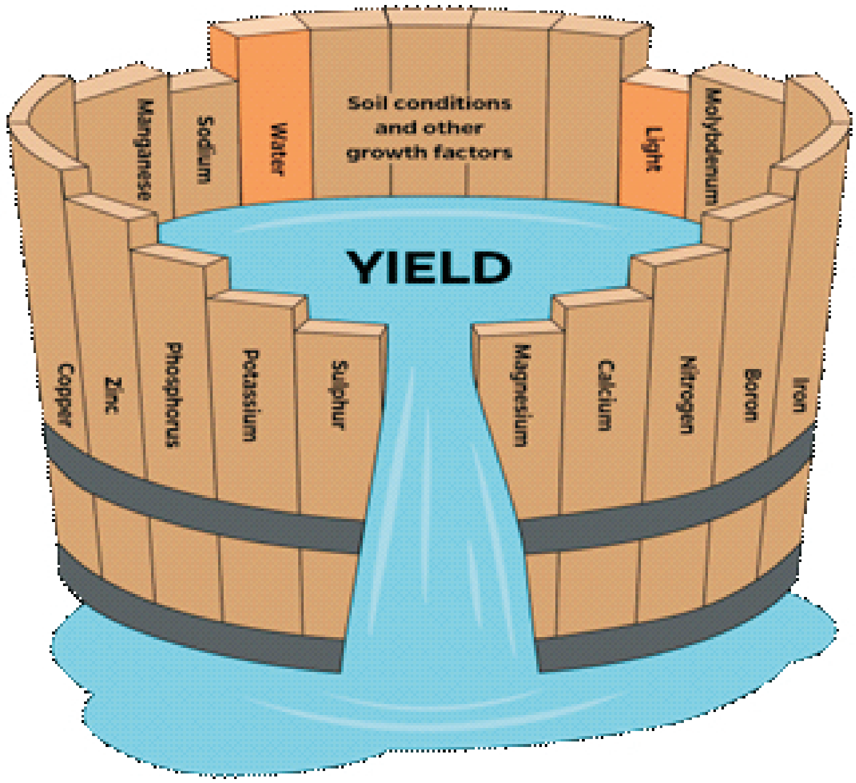

Figure21.1 Liebig's law of minimum

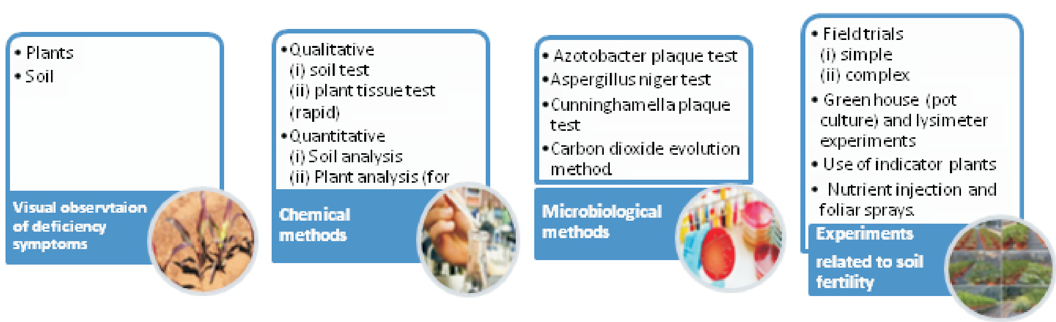

Figure 21.2 Soil fertility evaluation techniques

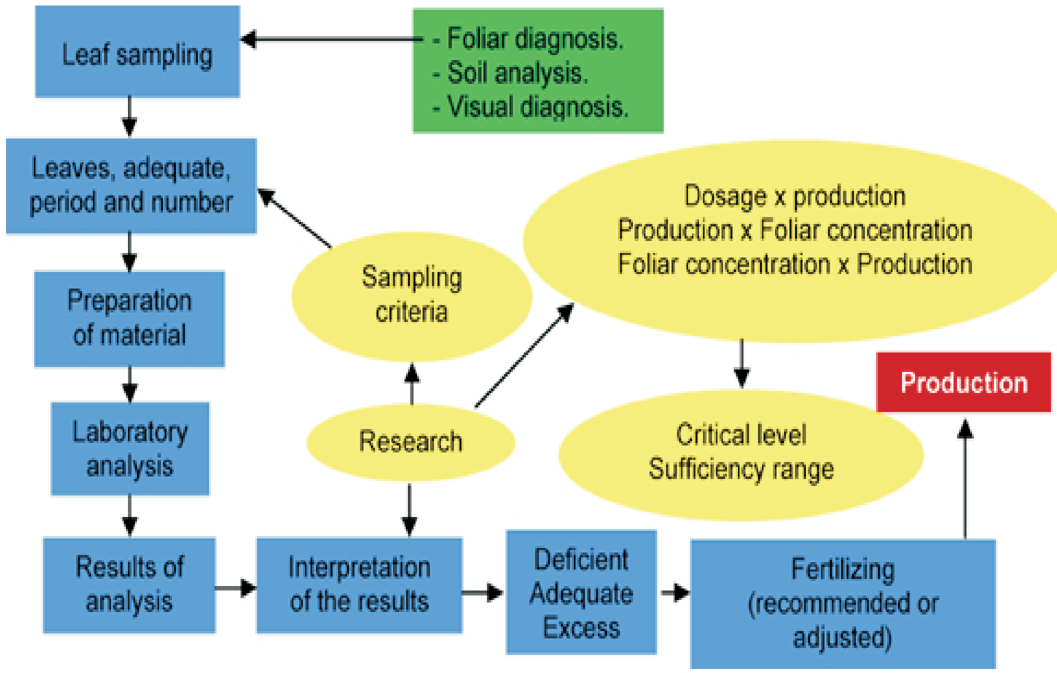

Figure 21.3 General steps for plant analysis in laboratory (Prado and Caione, 2012)

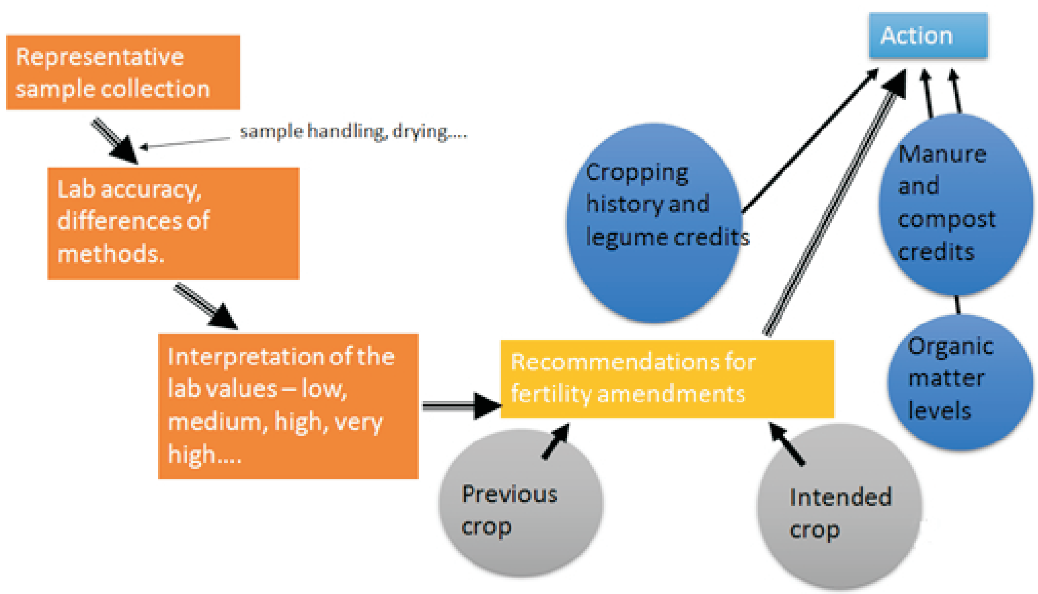

Figure 21.5 General steps in soil testing

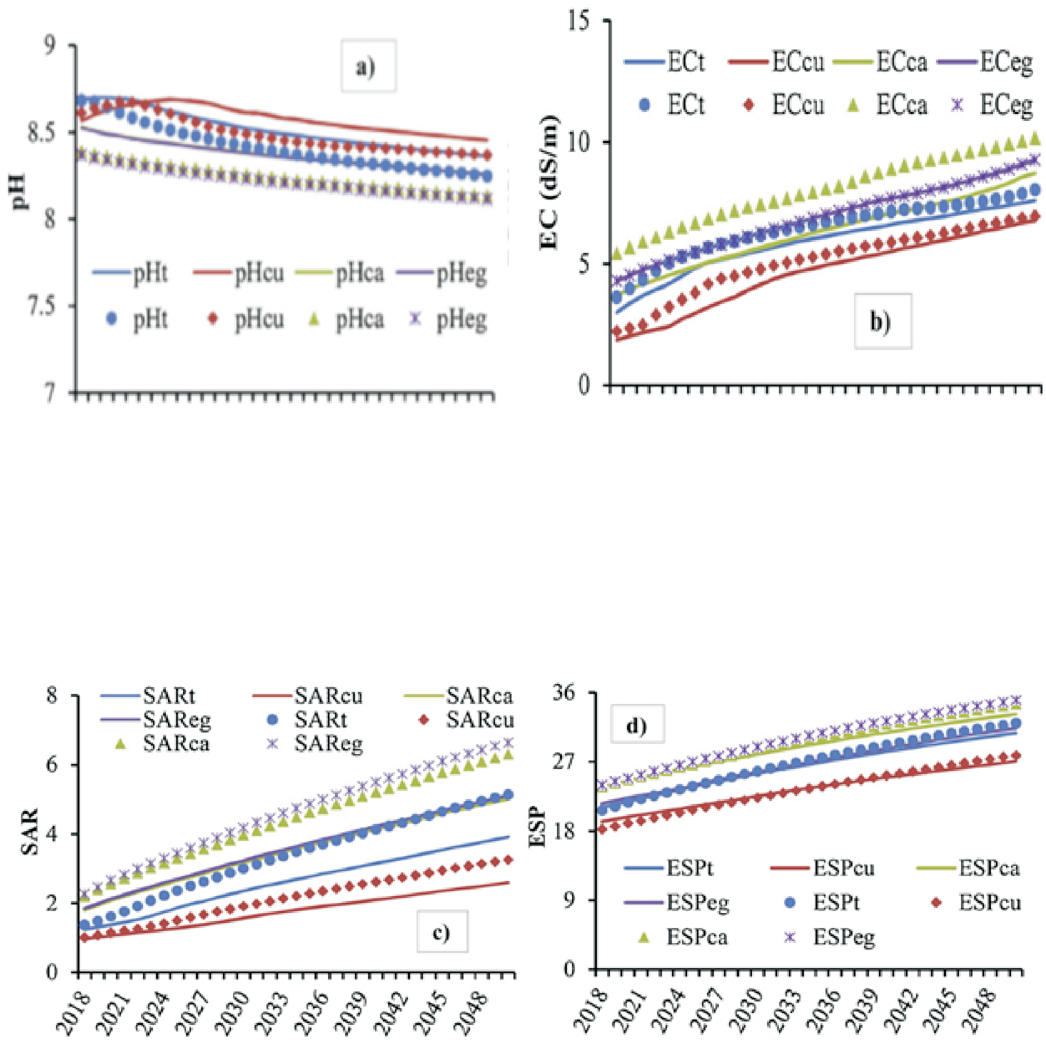

Figure21.6 "Simulated annual average values of a) pH b) EC (dS/m), c) SAR, and d) ESP in the sandy clay loam (solid lines) and sandy loam (dot points) soils under tomato (t), cucumber(cu), capsicum (ca), and eggplant (eg) crops irrigated with a blend of recycled water (Rw) and rain water (Gw) following a temperature based irrigation schedule" (Phogat 2020).

shortcomings on the aged leaves first. Calcium, sulphur, boron, and iron are the examples of immobile elements which do not move to newer leaves, and therefore, their deficiency symptoms manifest first on new leaves. The mobility of other nutrients is moderate.

Limitations:

- Experience is required because the symptoms of some nutrient deficiencies are difficult to distinguish.
- It may be too late in the season to administer corrective measures/ fertiliser by the time plant nutrient deficiency symptoms appear.
- Sometimes plants possess hidden hunger symptoms wherein, the plants do not show any symptoms even though a particular nutrient is deficient.
- One or more nutrients may be responsible for a visual symptom which may make it difficult to pin point the exact deficit nutrient or sometimes factors other than nutrient may be there.
- A particular nutrients' deficiency may be related to toxicity or imbalance of the other.
- Certain micronutrient shortages may visually resemble disease, insect, or herbicide damage.

Chemical Methods

Plant analysis is a useful supplement to soil testing since it is an indirect evaluation of soil. Plant analysis can be used to confirm nutrient deficiencies, toxicities, or imbalances, identify hidden hunger, evaluate fertiliser programmes, and determine element availability. A critical value approach is used for the interpretation of the plant analysis values. Plant nutrient concentrations are calibrated with respect to those required for optimal yields. If that concentration falls below 90 or 95% of the one required for maximum yield, the plants are designated as deficient and anything above that is considered as to as sufficient. Plant analysis is usually of two types:

I) Tissue testing

They are primarily used to confirm or predict the deficiencies of N, P, or K. Similarly. on-the-spot tissue tests have been developed for other nutrients (sulphur, magnesium, manganese and zinc) and the outcomes are categorised as low, medium, or high. It is possible to forecast or anticipate certain production problems occurring in the field by proper application of tissue testing. The cell sap nutrient concentration at the time of testing is considered to be a good indicator of the extent of effectiveness the plant is supplied with a particular nutrient.

Plant parts can be chopped up and reagents are used to extract the nutrients. Plant tissue can also be squeezed to transmit sap to filter paper using a garlic press, which is then mixed with color-developing reagents. The intensity of the colour developed is matched with the standards and used to determine nutrient content. Tissue tests are rapid, simple, and straightforward to perform and interpret. Many crops have already standardised for the time of sampling and the plant part to be sampled for tissue tests. Tissue tests can be performed 5-6 times per season, and concentrations can be monitored on-site. Nutrient demand can peak twice during the plant growing season: once when the plant is at the maximum vegetative growth and the other when it is at the reproductive stage. Tissue analysis can be a useful method for detecting nutritional deficiencies in plants provided few precautions are followed. The most important is that the correct plant part must be sampled, generally conductive tissue of the most mature leaf is used for testing. Secondly, the plant part must be sampled at the specified growth stage as the concentrations of most nutrients decreases dramatically as the plant matures.The critical growth stage is usually is at blooming or between bloom and early fruiting and even the time of the day is critical. For instance, if the supply of N is scarce, nitrate levels will be higher in the morning as compared to afternoon. The concentration of one nutrient can be influenced by the concentration of another, and the ratio of one nutrient to another (e.g., Mg/K, N/S, or Fe/Mn) can be a good indicator of plant nutritional status. In fact, for some plant species, elaborate mathematical systems for assessing the ratios or balance among nutrients have proven useful.

ii) Plant testing

Plant leaves are thought to be the centre of physiological activity. Changes in mineral nutrition is reflected in concentration of leaf nutrient. Plant testing is done using specific plant at a specific growth stage of the plant and plant part and the stage of sampling varies with the plant type. General steps for plant testing in a laboratory are presented in Fig. 21.3 (Prado and Caione, 2012).

Soil Testing

Understanding soil health and its maintenance is essential to maintain the crop productivity. A detailed physical, chemical, and biological analysis of the soils can give a true picture about the status of nutrients in soils as well as other physico-chemical properties of soil that can control the availability of nutrients to the plants. All of the nutrient reserves may not be in plant-available form, and of much use for the crops during their growth period. Hence, for the assessment or analysis of plant-available soil nutrients, such methods that have been tested/verified for the correlation between nutrients extracted and their plant availability should be employed. As a result, soil testing labs can go a long way in management of nutrients and enhancing crop productivity. A chemical soil test is much faster than plant analyses, and it also allows you to determine the deficiency in the soil even before planting the crop. Optimum soil test values can be correlated with relative yield of the crops (Fig. 21.4).

Objectives of soil testing:

- To provide a basis for fertilizer recommendation.
- To ascertain the production capability of soils.
- To classify soil based on relative nutrient levels that can be used for nutrient scheduling.
- To test the economic viability of the land for crop production.

For assessment of other limiting factors such as sodicity, salinity and acidity.

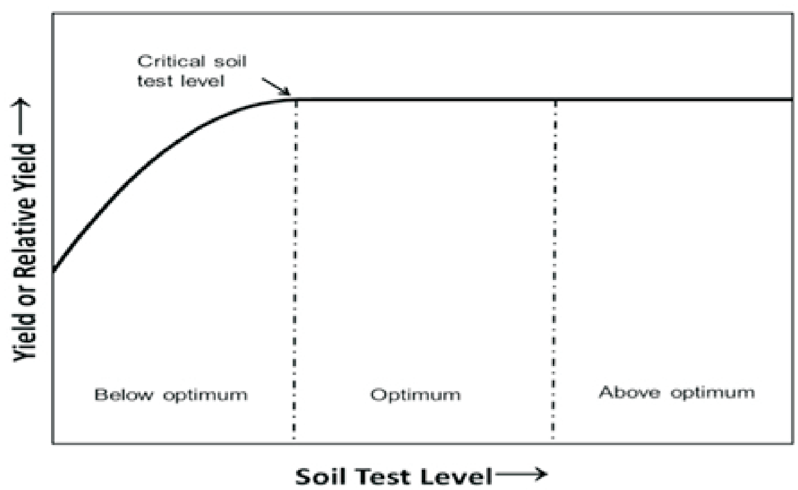

Fig. 21.4. Relative yield against soil test values

General Steps in Soil Testing:

Soil testing programme has multiple phases as mentioned below:

i. Soil sampling
ii. Sample preparation in the laboratory
iii. Selecting appropriate method of analysis for extraction and determination of plant available nutrients
iv. Interpretation of analytical values
v. Crop specific fertilizer scheduling/prescription

A general step wise description of a standard procedure adopted in soil testing and interpretation is given in Fig. 21.5.

Microbiological Methods

Certain microorganisms exhibit behaviour comparable to higher plants in the absence of nutrients. For instance, in the soil, based on the growth of *Azotobacter* or *Aspergillus niger,* the soils are classified in different categories i.e., very deficient and sufficient based on the amount of colony growth in the respective elements. Several techniques that use various types of microorganisms have been developed since then. Microbiological methods are faster, easier, and take less space than methods relying on the growth of higher plants.

Specific Issues Under Protected Cultivation and Their Management

In protected structures, soil must be viewed as a finite and non-renewable resource. Poor irrigation water quality and intensive irrigation increase the risk of salt accumulation in soil and their contamination in protected structures resulting in decline of crop productivity over time. Continuous, and specialised cropping pattern may adversely affect the biological activity of soils. Proper strategies should be developed for sustainability of soils under protected cultivation and soils' health must be monitored continuously through fertility evaluation measures including estimation of electrical conductivity and sodicity levels which can help in keeping a check over the loss of soil fertility. The first season of management of soil in a polyhouse is almost similar to that of in an open field. However, faster mineralization may result in accumulation of nutrient salts such as nitrates and in case the houses are not uncovered on a regular basis, salts can build up on the surface after a few years as there is no access to direct rainfall due to which excessive salts do not leach down, and irrigation is often not enough. Moreover, ions will inevitably be transported upwards due to capillary rise, resulting in higher salt concentrations and build up in the topsoil .

Salinization causes reduction in osmotic potential and toxicity of certain ions rendering the soil unfit for crop production. Salinization also affects nitrogen uptake, slows the plant development and reduces yield. Other physico-chemical properties such as pH, infiltration rate and nutrient availability may also get affected. Phogat et al., (2020) observed gradual decrease in pH values, though magnitude of reduction was very small (less than 5%) (Fig. 21.6). Lower pH of the irrigation water than that of the soil (initial) resulted in decreased soil pH as per the simulations by the year 2050. The lowest soil pH at the end of simulation was determined in crops that received the maximum water whereas, it was the highest for crops that received the least amount of water. Increase in soil electrical conductivity was also observed in soil due to continuous irrigation under protected cultivation. The increase in EC varied among different crops as a result of different irrigation requirements. The crops requiring higher number of irrigations had higher soil EC over the simulation period. Sodium adsorption ration (SAR) and exchangeable sodium percentage (ESP) exhibited similar trend.

Fernandez et al., (2010) reported that soil salinity was the outcome of the amount of saline water applied or the increase in evaporation. Hence, in case occurrence of salinity is expected, provisions should be made for leaching before the salt build-up is enhanced to beyond permissible levels (Shalhevet, 1994). Plants absorb only a small amount of salts and if there is no leaching the fraction leads to accumulation of salts in the soil. So, if the amount of water application is increased in each irrigation the surface salt contents can be reduced, as the salts percolate along with applied water beyond the root zone (Petersen, 1996). In clayey soils, leaching is less efficient than in the sandy soils as the movement of water is obstructed due to larger electrolyte dispersion in clay soils resulting in significantly more water movement within the soil without actually getting mixed with soil solution (Hoorn, 1981). The extent of leaching depends on soil properties, initial salinity and chemical composition of soluble salts, quality of irrigation, leaching methods, water-table depth, efficiency of drainage system, salt tolerance of crops to be grown, etc.

Phogat et al., (2020) reported that cultivation under greenhouse structures lead to build-up of sodicity or salinity if leaching fraction or gypsum is not applied. They advocated a leaching fraction of 15–20% for successfully move the salts beyond the reach zone. Gypsum, organic materials and calcium may be applied to over come sodicity build-up (Awad et al., 2019). Proper drainage should be provided before leaching with water to remove sodicity and irrigation water must be low in sodium.

This will help in replacing sodium ion from the exchange complex by the calcium ion, and the irrigation water will leach the displaced sodium.

Nutrient Management

The key to manage greenhouse nutrient is regular checking of plants (Table 21.1). Examine the foliage for colour, vigour and root health. Occasionally, the deficiency could be due to root damage, pest attack, disease or poor water management techniques. This may result in appearance of deficiency symptoms in spite of sufficient quantities of macro and micro nutrients in the soil and proper fertilizer scheduling. Therefore, root inspection is critical part of nutrient management apart from other soil fertility evaluation techniques.

Table 21.1: Common deficiency symptoms and their remedies under protected structures.

S.No.	Symptoms	Deficiency	Solution
1	Light green to yellowish plant	Sulphur	Apply $MgSO_4$ at 0.3-0.6 g/L of water
2	Growing tip is lost, elongate and brittle young leaves	Boron	Decrease hum idity level in the protected structures. Borax solution can be used.
3	Growing tip is alive, but young leaves are distorted. Leaf necrosis on edges may be observed.	Calcium	Decrease humidity level in the protected structures. If it does not improve Ca uptake, spray calcium chloride solution.
4	Interveinal chlorosis in young leaves progressing to yellow to white.	Iron	pH of the media need to be checked. If required may be adjusted by acid forming fertilizer. Iron chelates can be used.
5	Leaf chlorosis in older leaves	Nitrogen	Electrical conductivity of fertilizer solution need to be checked, injector nozzles to be inspected and leaching can be reduced.
6	Purple coloured older leaves	Phosphorus	Check media for P levels. Fertigate with P at 50-100 ppm.
7	Edge burn type symptoms in older leaves	Potassium	Check the potassium level in fertigation solution as well as inspect nozzles to see if they are working properly

Fertilizer excesses

Many growers believe that if a plant fails to thrive despite apparently favorable circumstances, the problem can be rectified by applying fertilizer. Such practices result in immeasurable crop damage or loss as the problem is due to excessive fertilizer application. The consequences of applying unneccesarily additional fertilizer can be severely adverse. Difference between safe and injurious nutrient levels isn't always significant, and the margin of safety can be razor-thin. Proper testing needs to be adopted if there is any doubt regarding injurious levels of nutrients.

Remedial measures for excess fertilizer

Fertilizer toxicity should be immediately addressed by removing the excess. Excess nitrogen may be leached and straw mulch can be used. Leaching is also effective to remove potassium from coarse textured soils but may nearly be impossible in fine textured soils. Phosphorus is relatively immobile in the soil and cannot be leached out and therefore, amendments eg. iron sulphate or lime can be applied. Calcium can be neutralized by acidifying the soil and excessive iron to be treated by raising soil pH or by adding phosphorus. Excessive sulphates and boron can be compensated by avoiding the use of sulphate fertilizers and application of solution of sodium silicate. Excess aluminium is treated by raising the pH or phosphorus addition whereas, remediation of other soluble salts may be done by leaching.

Fertigation

Fertigation is an excellent way to improve the long-term viability of protected structure production because it regulates both soil water movement and nutrient supply. Adjusting irrigation strategy is essential since mineral losses to the groundwater table or surrounding surface water are driven by vertical water transport in the soil. Using a fertigation device, a grower can administer nutrients accurately and evenly in the root zone. Small amounts of fertiliser can be applied to plants by fertigation when the crop is still in vegetative stage and with the rise in nutrient demands, the dosage is increased whereas, it is decreased as the crop cycle nears maturity.. The most common nutrients applied by fertigation are nitrogen, potassium, phosphorus, and magnesium (Table 21.2). However, micronutrients too can be applied through fertigation setup. Nutrient solubility and mobility along with quality parameters of irrigation water such pH, EC and mineral content needs to be considered for fertigation.

Advantages of Fertigation

- Helps supply both water and fertilizer simultaneously.
- Increases yield by 25–30 per cent.
- Application and distribution of fertilizers becomes uniform and accurate saving the fertilizers by 25–30 per cent and nutrient requirement may be modified as per crop.
- Lower pH can help in avoiding clogging of drippers.
- Major and micro nutrients can be supplied together with irrigation.
- Requisite amount of fertilizers can be injected in concentration.
- Saves time, labour and energy.
- Complete control and remote access of your crop feed.
- Less dependence on precious time of grower.

Table 21.2: Composition of major nutrients in different fertilizers commonly recommended for fertigation

S. No.	Fertilizer	N-P-K
1	Urea	46-0-0
2	Ammonium Nitrate	34-0-0
3	Ammonium Sulphate	21-0-0
4	Calcium Nitrate	16-0-0
5	Potassium Nitrate	13-0-46
6	Potassium Chloride	0-0-60
7	Potassium Nitrate	13-0-46
8	Potassium Sulphate	0-0-50
9	Phosphoric Acid	0-52-0
10	NPK	19-19-19 20-20-20

Compatibility

Since multiple nutrient types are to be applied at the same time through the fertigation set up, their compatibility is of utmost important. Mixing multiple water-soluble fertilizers sometime lead to their precipitation rendering the mixture useless for fertigation. Therefore, different nutrient solution should be prepared separately in independent containers. A compatibility chart for different fertilzers is given in (Table 21.3) (http://www.ncpahindia.com).

Table 21.3: Compatibility chart for different fertilizers

S. No.	Fertilizers	Urea	Ammonium Nitrate	Ammonium Sulphate	Calcium Nitrate	Mono Ammonium Phosphate	Potassium Nitrate
1	Urea		C	C	C	C	C
2	Ammonium Nitrate	C		C	C	C	C
3	Ammonium Sulphate	C	C		LC	C	LC
4	Calcium Nitrate	C	C	LC		NC	C
5	Mono Ammonium Phosphate	C	C	C	NC		C
6	Potassium Nitrate	C	C	L	C	C	

C = Compatible, NC = Not Compatible, LC = Limited Compatible

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22. WATER STRESS MANAGEMENT – NEED FOR ENHANCING WATER PRODUCTIVITY

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Abstract: India placed thirteenth among the world's 17 'extremely water-stressed' countries. Both surface water and groundwater in India was highly exploited. In India, out of 5723 geo-physical blocks, over 1000 blocks were over exploited for groundwater use. Under water-deficit conditions, higher temperatures coupled with a reduced water supply are likely to reduce crop production. For rainfed crops, enough soil moisture is very important during both planting and the growing period to avoid water stress and reduction in yields. Water in agriculture is saved by reducing irrigation water applied to the crops and/or used by the plants as evapotranspiration (ET) by a number of water saving technologies. There is no reduction in the yield in case the irrigation water saving interventions are concomitant with mulching, tillage and application of additional nitrogen. Understanding of water budgeting helps in improving irrigation strategies for conserving irrigation water and reducing ET; and provides a foundation for efficient water resource planning and management. Measurement of water productivity/use efficiency is an important tool for selection of soil and crop management technologies for enhancing yield as well as water savings.

Introduction

Fresh water constitute only 3% of the Earth's total water and most of it is in icecaps and glaciers (69%) and groundwater (30%), whereas, lakes, rivers and swamps in combination account for only a small fraction (0.3%) of the Earth's total freshwater reserves (Fig. 22.1).

Considering the pace of the population growth and the rise in water use per capita, the world's fresh accessible water situation is deteriorating at a dismal pace. Increased use of fresh water in agricultural and non-agricultural activities in the past few decades has caused an alarming rate of ground water depletion in many regions of the world (Fig. 22.2). This threatens the sustenance of crop production and endangers the food security. One-quarter of the world's population faces extremely high levels of baseline water stress (Fig. 22.3) i.e. the ratio of total annual water withdrawals to total available annual renewable supply, accounting for upstream consumptive use. Higher values indicate more competition among the users. India has been placed at thirteenth position among the world's 17 'extremely water-stressed' countries, according to the Aqueduct Water Risk Atlas released by the World Resources Institute (WRI).

A region is said to be under 'water stress' if the demand for water exceeds the available volume or poor quality restricts its use. The World Bank too had warned about the region's water stress last year. There were countries "withdrawing water from underground reservoirs faster than it could be replenished and were essentially living beyond their means". 'Extremely high' levels of water stress refers to the fact that on an average 80% of the available water in a country is used in irrigated agriculture, industries and municipalities every year. Both surface and ground water was highly exploited in India. In India, out of 5723 geo-physical blocks, >1000 blocks were over exploited for groundwater use which runs 94.5 per cent of all minor irrigation schemes in India. However, the government must focus on more sustainable surface water schemes. Water-table decline has serious economic implications. It has forced the farmers to install submersible pumps, increasing their costs and preventing groundwater recharge. In Indo-gangetic plains, the region famous for green revolution, groundwater is falling rapidly eg. in Punjab, groundwater levels decreased at the rate 0.5-1.0 m $year^{-1}$ in the last 20 years. Such scenario may lead to fight between different states over water and even within states. Delay in taking suitable measures to ensure sustainable groundwater usage may lead to serious consequences such as reduction in agricultural output and shortage of potable water, leading to extensive socio- economic stresses. The gap between supply and demand may widen due to climate change and drought-like situations, coupled with uncontrolled groundwater extraction. Reusing wastewater could help countries overcome water stress and become water secure, the report said.

Per capita annual water availability

The per capita annual water availability in India has declined to 1,508 cubic meter in 2014 from 5,177 cubic meter in 1951 and is estimated to further decline to 1,465 cubic meter by 2025 (Fig. 22.4).

There is need to use suitable technology and crop diversification to reduce water consumption. If the water availabilty declines to around 1,000-1,100 cubic meters, the country can be declared as water stressed and this situation may lead to scuffles between and within different states over water. Out of total net sown area of 140 million hectare, only 48.8% is under irrigation and rest is rainfed and of the net irrigated area of 68.32 million hectare, about 60% is irrigated through groundwater (Fig 22. 5).

The knowledge about the sources and sinks as well as recycling of water is a prerequisite to understand water saving. In agriculture the water received from precipitation or groundwater withdrawal is used for irrigation. A part of that is used by the crop to meet evapotranspiration (ET) demand and is lost as transpiration (T) from plants and evaporation from soil (E) to the atmosphere which constitutes a sink, and from where it cannot be reused. The remaining part drains to surface and subsurface storages and other sinks such as aquifers, inland seas and oceans which may be sink or source depending upon the condition of water. Storage of deteriorated and poor quality in subsurface will act as sink. whereas, good quality water fit for reuse becomes a source. So, any reduction in water that leads to those sinks, from where it cannot be reused, is called water saving.

Knowledge of water use efficiency is vital for selection of yield-enhancing soil and crop management technologies. Another objective criterion is the agronomic one, where yield is the output and irrigation water is input, and in this case the water efficiency is called *water productivity.* Though WP is commonly used, but it has some limitations.

(i) It is not only the irrigation water that contributes towards dry matter/yield, but rain water and water by capillary rise also contributes.

(ii) Calculation of irrigation water productivity of a crop or cropping system, the irrigation water applied for preparation of seed beds is not taken into account (for computing total irrigation water applied). These amounts are of greater importance in various crops. The concept of water productivity is objectionable as it is not useful in agricultural water management.

(iii) When crop dry matter is output and transpired water is input, the efficiency is called *water use efficiency (*WUE). As most of the applied water (99%) is transpired and only a small fraction is retained by the plant, therefore, water use efficiency is the reciprocal of transpiration ratio, the mass of water transpires per unit mass of dry matter produced. But under field conditions, it is very difficult to separate out transpiration from evaporation.

As a thumb rule, only 10% water uptake of a crop plant results into/ produces a fresh weight increase, while 90% is transpired. It forces one to think that whether such a high transpiration rate is really needed for optimum yield. In case of tomato, higher planting density resulted in a 10% yield increase, whereas, transpiration increased by 16% hence, there is no strict relationship between transpiration and yield. Several experiments with greenhouse fruit plants and vegetables have shown that transpiration can be reduced by 10-30%, without reduction in yield. Hence, rather than transpiration, evapotranspiration is used to calculate WUE. The WUE is also called crop water productivity (CWP) or water productivity based on evapotranspiration (WP_{ET}) as WUE or CWP or $WP_{ET} = Y_{act.}/ET_{act}$

In agriculture, water is saved for two purposes i.e for decreasing groundwater draft and for preventing /ameliorating water table decline.The reduction of irrigation water via decreasing groundwater draft is called dry or apparent water saving as it may be recycled within the basin (unless it is polluted). In reality, reduction of irrigation water is not water saving; but it lowers the cost of production of crops, saves energy and reduces the carbon emission. In fact, reducing ground water draft by applying less irrigation water and increasing water application efficiency through various means i.e. - land leveling by laser, optimum plot size, use of micro irrigation techniques, better scheduling and method of irrigation etc. save energy not water. But it will definitely enhance water productivity.

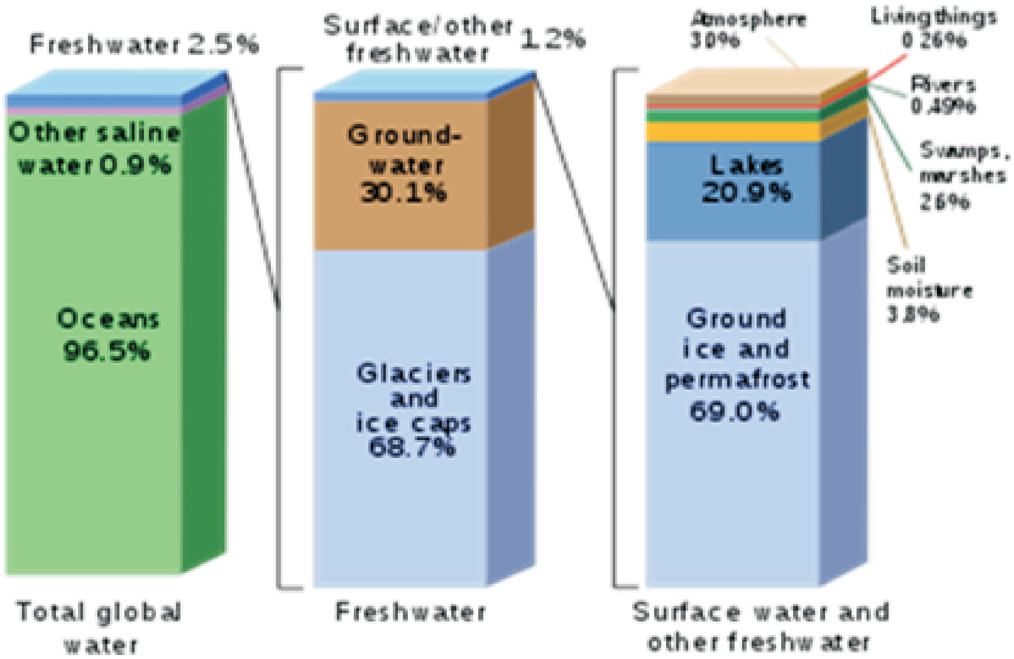

Figure 22.1 Status of Earth's fresh water

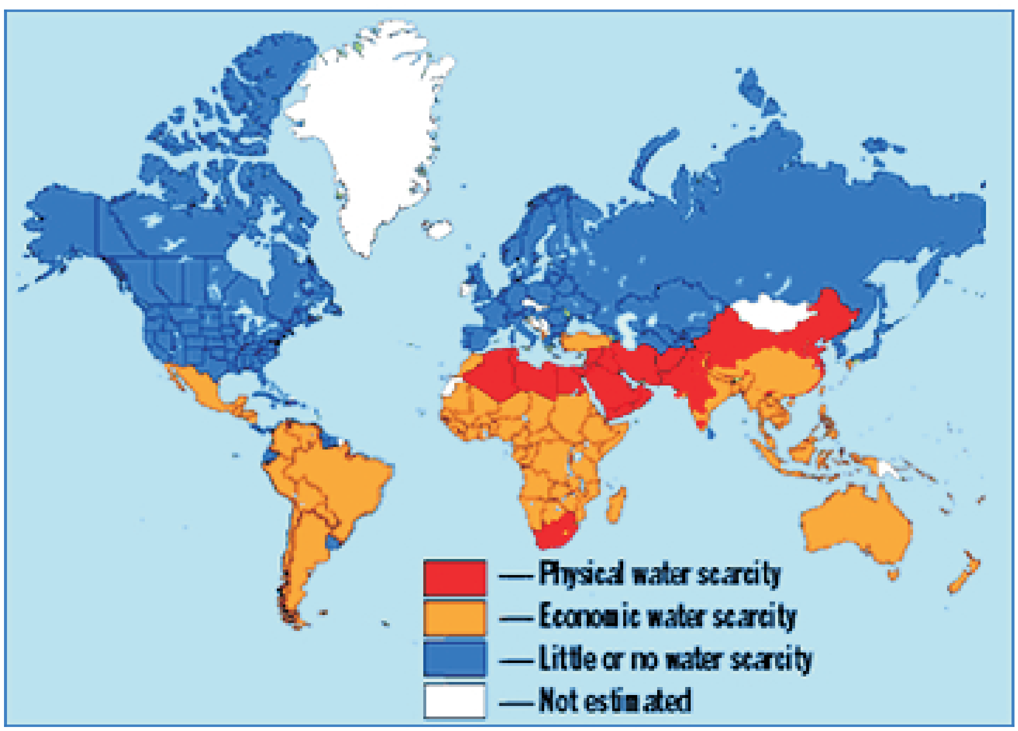

Figure 22.2 Global status of water scarcity

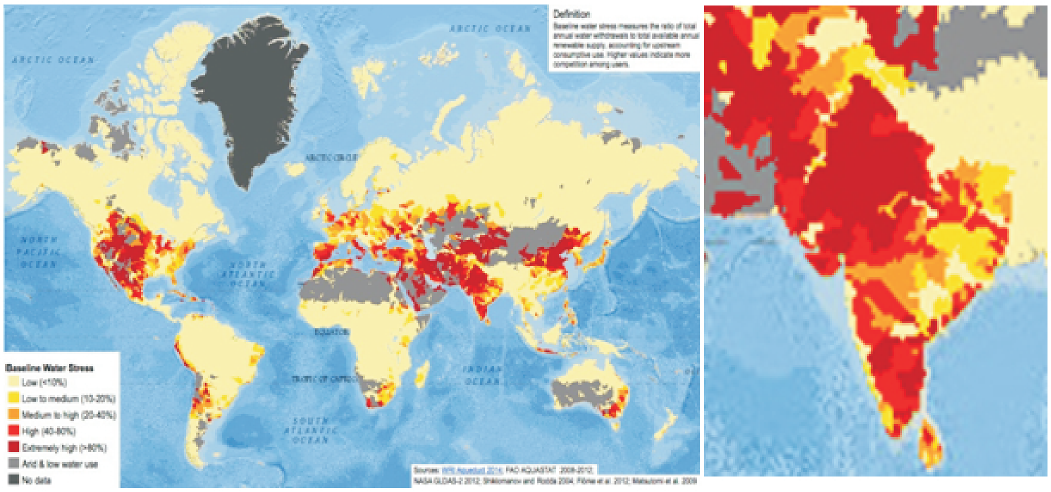

Figure 22.3 Baseline water stress

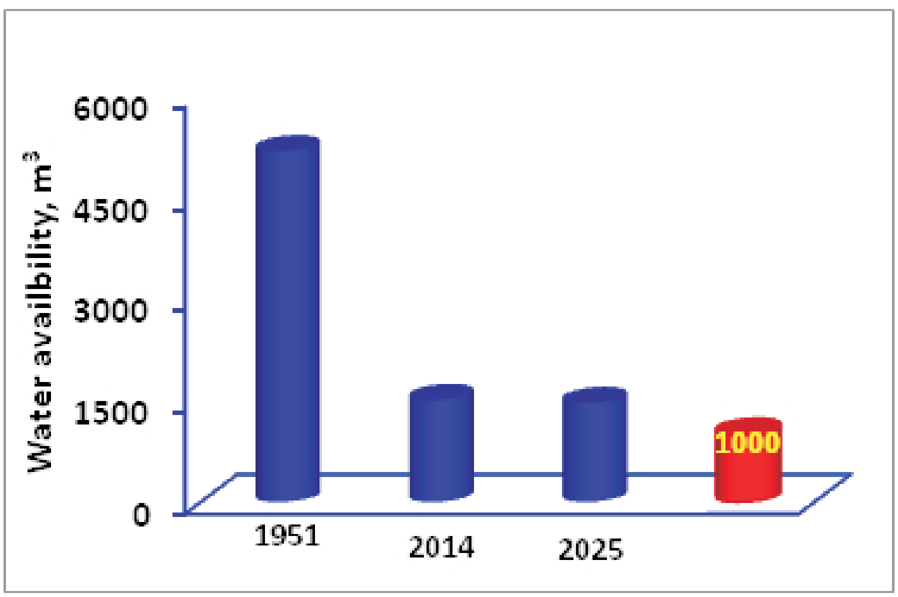

Figure 22.4 India's per capita annual water availability (m^3)

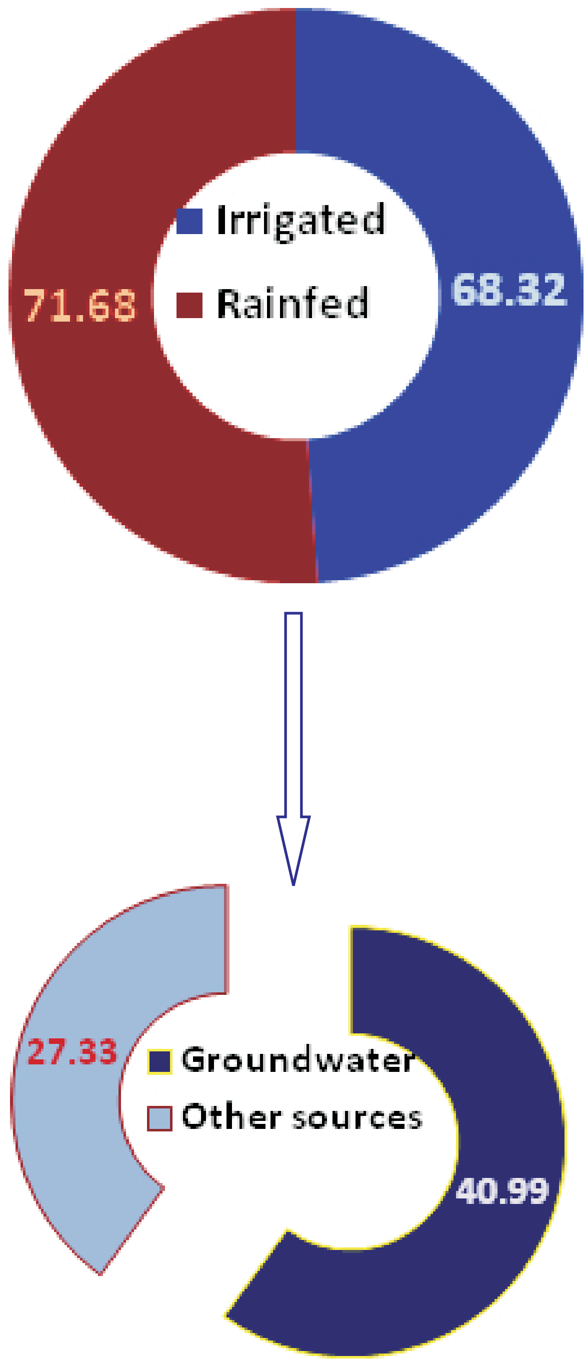

Figure 22.5 Percent Irrigated and rain-fed area in India

So, to manage groundwater level, efforts needs to be directed to increase water supply and its entry into the soil by increasing surface water supply from canals, reducing runoff, increasing infiltration of the surface soil by modifying soil surface conditions (more in direct seeded rice than puddle) and drainage in vadose zone; and by encouraging real water saving by reducing evapotranspiration and by reducing unproductive water loss by soil water evaporation.

Evapo-transpiration can be reduced through - Crop diversification i.e. replacing high ET crops with relatively low ET (Table 22.1-22.5), selecting proper irrigation schedule (Table 22.2), synchronizing crop period with lower evaporative demand by shifting planting time, adopting shorter duration variety and micro/subsurface irrigation (Table 22.3), and using crop residue as mulch. Such practices results in real water saving which ameliorates water table decline.

Table 22.1: Information on water use (ET) efficient crops

Crop	ET (mm)	Water use efficiency (kg m^{-3})
Rice	600	1.08
Maize	480	0.94
Cotton	600	0.38
Sugarcane	1350	2.68
Wheat	380	1.24
Raya	280	0.54
Chickpea	320	0.47
Sunflower	550	0.40

Table 22.2: Selection of proper irrigation schedule

Treatment	Irrigation water (mm)	Grain yields (t ha^{-1})
Wheat		
Fixed stages -5	350	4.3-4.5
IW/PAN-E 0.9	225-280	4.1-4.3
Rice		
2- day drainage	1128-1480	6.4-6.8
SWT- 16 kPa	992-1020	6.2-6.3

Planting time

Shifting the planting time of crops from high to low ET periods is likely to enhance WP. The ET of rice transplanted on June 15 is 100-140 mm less than that of transplanted on May 15. Shifting transplanting date in rice saves water by reducing soil water evaporation, shorter duration variety by reducing both the evaporation and transpiration, whereas, irrigation scheduling reduces neither evaporation nor transpiration.

Use of micro irrigation techniques (Drip irrigation)

The on-farm irrigation efficiency is 90% by drip irrigation system against 40-45% in surface irrigation method. Some examples of irrigation water reduction and increase in yield are cited in table 22.3.

Table 22.3: Percent irrigation water reduction and increase in yield through drip irrigation in various crops.

Crop	Irrigation Water reduction (%)	Increase in yield (%)
Kinnow	40	35
Tomato	41	56
Potato	38	52
Brinjal	44	27
Wheat	31	32
Spring maize	40	41
Sunflower	53	11

Table 22.4 Effect of using crop residues as mulch on evaporation.

Water balance component (mm)	Maize		Sugarcane	
	No-mulch	Mulch	No-mulch	Mulch
Irrigation water	180	113	755	475
Evapotranspiration	492	333	1361	1048
Evaporation	259	74	349	113
Transpiration	233	259	1012	1035
Drainage	284	358	205	170

Table 22.5 Effect of crop diversification on evapo-transpiration

Replaced Crops	Suggested Crops	Total ET-based water saving(M ha-m)
Rice	Pulses (1.0 M ha)	0.15
	Pulses (0.5 M ha) + Maize (0.5 M ha)	0.135
	Basmati rice (1.0 M ha)	0.10
Wheat	Oil seeds (1.0 M ha)	0.10
	Oil seeds (0.5 M ha)+ Gram (0.5 M ha)	0.08

There is an urgent need to look for measures that sustain current level of crop yields with reduction in soil water evaporation component of hydrological balance during cropped and non-cropped periods. With plentiful water, the objective was to maximize land productivity. Now with limited water, our aim has shifted to maximize productivity per unit of water. Protected cultivation of horticultural crops including vegetables would be helpful to maximize productivity. Protected cultivation played a vital role in enhancing quality production per unit area in shorter cycle with less water. In the Himachal Pradesh, about 250 ha area is under protected cultivation with approximately 10000 polyhouses constructed with the financial support from Government. Polyhouses with drip irrigation system and misters can reduce the amount of water required for cultivation, evaporation losses can be reduced through mulching, and fertilizer use may be minimized by directly applying them in the right dose to the root zone of the plant. Rainwater harvesting provides a wonderful opportunity to supplement the water requirement of a polyhouse. The run-off of rainwater from the top of a polyhouse can be collected and reused inside the poly-house through drips and misters. The water requirement for a six-month old crop can easily met from the catchment area of the polyhouse roof itself, thus making it self-sufficient and sustainable. There is a need to reduce the consumption of water in the agriculture sector as per the Honourable Prime Minister call for per drop more crop.

Conclusion:

Rethinking is required on some of the following options to combat with crop water stress and also for enhancing water use efficiency following the measures suggested below:

- A blanket ban on growing crops during dry and hot summer seasons to prevent indiscriminate exploitation of groundwater.
- Encouraging the surface retention of crop residues as mulch to reduce unproductive soil water losses rather than burning it to cause environmental degradation and loss of nutrients.
- Promotion of micro-irrigation technologies, construction of polyhouses and linking subsidies with the production of high value crops like vegetables, horticultural crops.
- There is a need to double the area under micro-irrigation from the current level of 9 million hectares.
- There is need for scheduling of irrigation process and use of technologies like moisture sensor and other softwares.
- Need for constructive use of water especially groundwater, rainwater harvesting and use of waste water in irrigation.

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23. PLANT WATER INDICES FOR IRRIGATION MANAGEMENT

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Abstract: Irrigation system is one among the most important factors affecting the yield and quality of field crops. Water should be applied in proper quantum with accurate time operation. Hence, water operation may be a key to avoid moisture stress during the crop growth stages. New water- conserving irrigation operation practices are being enforced to enhance the yield and quality of crops. Under irrigation operation practices, crops are constantly exposed to some extent of water stress to work out the threshold water deficiency position which won't have an ill effect on growth and yield. In addition to this, crop/plant response and adaption mechanisms to new irrigation practices have to be understood for the successful perpetration of new irrigation practices. To, comprehend this, water stress indicators that are largely apprehensive of water stress and that can help in early detection of water stress need to be linked. Plant water stress indicators are relatively effective in determining the water stress in crops because they take under consideration the accretive effect of water stress due to declining soil water status and increased evaporative demand of the atmosphere. Water stress quantification using plant - based approaches involves direct measures of several aspects of plant water status and circular measures of factory processes which are sensitive to water deficiency. In this chapter, different plant based water stress indicators are critically reviewed for their efficacy to determine the level of water stress and their felicity for irrigation scheduling in crops.

Introduction

Conventional methods for estimating crop water requirements and monitoring crop stress rely on the measurement of soil moisture, climatic variables and crop characteristics (crop height, phenology, etc.). Depending upon the availability and feasibility of instrumentations, most of the conventional methods involve intense data collection and analysis, which are time-consuming, destructive and involve soil water balance computations. However, still these may not represent actual crop water need or the overall status of the field.

The first usually adopted approach use is the plant itself as an indicator of irrigation need. The still frequently adopted approach even today, is to base irrigation on visible wilting. An efficient plant-based irrigation program depends on whether whatever measurement is made is sensitive enough to properly assess the water deficit for the specific plant/crop (Jones, 2004). For example, plants with strong endogenous control systems maintain a stable leaf water status over a wide range of evaporative demand or soil water supplies, and in some cases, by the time wilting becomes apparent, a substantial proportion of potential yield might have already been lost (Slatyer, 1967). Therefore, one cannot use plant water status as the index for irrigation scheduling. Hence, more rigorous and more sensitive measures of checking plant water status are required.

Although relative water content (RWC), as proposed by Barrs (1968) is widely used to measure the water status and it does not require sophisticated equipment also, but it is often argued that water potential, especially of the leaves (ψleaf) is a more rigorous and more generally applicable measure of plant water status (Slatyer, 1967; Jones, 1990b). However, RWC has the advantage that it can be more closely related to cell turgor, which is the process directly driving cell expansion, than the total water potential (Jones, 1990b).

The plant water status especially the leaf water status, is usually controlled to some extent by means of stomatal closure or other regulatory mechanisms hence, it argues against the use of such measures, especially in strongly isohydric species. The use of leaf water status as an indicator of irrigation need was reported to have homeostasis of leaf water potential between different soil moisture regimes and rapid temporal fluctuations are often observed as a function of environmental conditions such as passing of clouds (Jones, 1990). This makes the interpretation of leaf water potential as an indicator of irrigation-need doubly unsatisfactory. In spite of the fact that use of leaf water status as described above, leaf water potential can, when corrected for diurnal and environmental variation, provide a sensitive index for irrigation control (Peretz et al., 1984).

As a partial solution to the variability of leaf water status, the xylem water potential or stem water potential (XWP) has been proposed as a more useful and more robust indicator of water status. It is measured by using a pressure chamber on leaves enclosed in darkened plastic bags for some time before measurement and allowed to equilibrate with the xylem water potential (McCutchan and Shackel, 1992). Predawn leaf water potential (as ψleaf should largely equilibrate with ψsoil by dawn) is a better estimator of the soil water potential. Unfortunately, it is often found to be insensitive to variation in soil moisture content (Garnier and Berger, 1987). Moreover, it is not convenient for irrigation scheduling as routine measurements as predawn are difficult to obtain, and at the best these can only be obtained daily. Jones (1983) suggested another alternative i.e. the indirect estimation of an effective soil water potential at the root surface of transpiring plants based on measurements of leaf water potential and stomatal conductance during the day, he emphasized that this should have significant advantages over predawn measurements. This approach has been successfully tested by Lorenzo-Minguez et al. (1985).

None of the above plant-based methods are well adapted for automation of irrigation scheduling or control as in these it is difficult to measure any of the variables discussed. It may be possible to use automated stem or leaf psychrometers (Dixon and Tyree, 1984), but these instruments are unreliable.

Measurement of plant water status

There are several methods of measuring the water status of plants (Turner, 1981) but all are suitable for irrigation scheduling e.g. the measurement of relative water content is not suitable for irrigation scheduling as it requires rehydration, drying and accurate weighing of samples in the laboratory for several hours to know the result. The measurement of the water potential of the plant is possible with either the pressure chamber (Turner, 1988) or thermocouple psychrometer (Boyer, 1987). The pressure chamber is the most widely used technique in the field and development of temperature compensating in situ psychrometers for irrigation scheduling is highly now well advanced (Campbell and Campbell, 1974). The measurement of leaf water potential is not a good measure of the physiological or metabolic activity of the plant e.g. in lupin leaf expansion and leaf assimilation are both reduced by more than 75% without any decrease in leaf water potential (Henson et al. 1988; Turner & Henson, 1988) and there is evidence that in some species stomata get closed to maintain a high leaf water potential (Turner et al., 1984). Furthermore, plants can adapt to develop water deficits slowly, so that the water potential, at which physiological activity is affected, is changed (Turner, 1986). One such mechanism is osmotic adjustment where the plant accumulates solutes in response to slowly decreasing leaf water potentials thereby maintaining the turgor pressure (Turner and Jones, 1980). For e.g., sugarcane adjusts its osmotic pressure diurnally by about 0.3 MPa and that unirrigated sugarcane can adjust osmotically by about 0.4 MPa in response to a declining soil water potential (Soopramanien and Batchelor, 1987).

Several indirect methods for measuring or monitoring water status have been developed as an alternative to direct measurement. The general behaviour of such methods have been compared by McBurney (1992) and Sellés and Berger (1990). In general, these indirect methods also suffer from the same constraints as the direct measurements of leaf water status. However, in certain circumstances some of these have been developed into commercial systems. Some of these approaches are reviewed below:-

a) Leaf thickness and rolling:

A number of instruments are available for the routine monitoring of leaf thickness which, decreases with the decrease in turgidity. It can be measured through direct measurement using linear displacement transducers (e.g. LVDTs [Burquez, 1987; Malone, 1993] or capacitance sensors [McBurney, 1992]) or through measurements of leaf's superficial density' using β-ray attenuation (Jones, 1973). However, mostly the leaf thickness is less sensitive to changes in water status than is the leaf water content because, especially with younger leaves, a fraction of leaf shrinkage is often in the plane of the leaves rather than in the direction of the sensor (Jones, 1973).

Leaf rolling in many grasses is sensitive to leaf water status beyond a threshold value. A leaf rolling index (Begg, 1980) may be preferable in irrigation scheduling. The leaf rolling index is the width of the rolled leaf as a fraction of the unrolled width at the point of maximum leaf width. The finding of Oosterhuis and Walker (1987) concluded that stomatal resistance was a useful indicator of water deficits in wheat and soybean, whereas, canopy temperature and leaf rolling were the most suitable methods in rice because of their speed and non-destructive nature and were as accurate as traditional methods of measuring plant water status such as the pressure chamber (O'Toole et al., 1984).

These methodologies have the limitations for irrigation schedule, which deter the use of measures that cannot be automated because they result from labour-intensive and discontinuous processes. There are some techniques to determine water consumption by an individual plant.

b) Stem and fruit diameter:

Stem and fruit diameters fluctuate diurnally in response to changes in water content hence have most of the same disadvantages as other water status measures. Nevertheless, the diurnal dynamics of changes in diameter, especially of fruits, have been used to derive rather more sensitive indicators of the irrigation need. The magnitude of daily shrinkage has been used to indicate water status and comparisons of diameters at the same time on succeeding days give a measure of growth rate (Jones, 1985; Li and Huguet, 1990; Huguet et al. 1992). Several workers have achieved promising results for low-frequency irrigation scheduling by the use of maximum daily shrinkage (MDS). Fereres and Goldhamer (2003) showed that MDS was a more promising approach for automated irrigation scheduling than was the use of stem water potential for almond trees, while differences in maximum trunk diameter were also useful in olive (Moriana and Fereres, 2002). Sellés and Berger (1990) reported that variations in trunk diameter or stem water potential were more sensitive indicators of irrigation need than was the variation in fruit diameter. This was probably due to poor hydraulic connection between fruit tissue and the conducting xylem.

c) γ-ray attenuation:

A related approach to the study the changes in stem water content was the use of γ-ray attenuation (Brough et al. 1986). This approach was very sensitive, but safety considerations and cost have limited its further application.

d) Sap flow

The development of reliable heat pulse and energy balance thermal sensors for the sap-flow measurement in the stems of plants (Cermak and Kucera, 1981; Cohen et al., 1981; Granier,1987) opened up an alternative approach for irrigation scheduling based on measurements of sap-flow rates. At a particular soil moisture level, sap flow rate is highly sensitive to solar radiation followed by vapour pressure deficit and then by air temperature (Yang et al., 2019). Sap-flow rates may be sensitive to water deficits especially to stomatal closure, hence, sap-flow measurement was used for irrigation scheduling and control in a diverse range crops. Changes in transpiration rate, as indicated by sap flow, are largely determined by changes in stomatal aperture, however, it is influenced by other environmental conditions i.e. humidity. So, changes in sap flow can occur without changes in stomatal opening. It infers that, sap-flow measurement is well adapted for automated recording so, potentially automated control of irrigation systems, may be little difficult to determine the correct control points for any crop.

The various techniques to obtain sap flow can be separated into three groups i.e. a) heat pulse method, which tracks the movement of a short heat pulse in the sap flow; b) heat balance method, which measures the sap movement, by heat transport, out of a controlled heat source; and c) thermal dissipation, which infers the heat dissipation by sap flow through an empirical relation.

Fernández et al., (2001) reported that the sap flow technique by heat pulse method was suitable for estimating the dynamics of transpiration changes in the water behaviour of trees. Santos et al., (2005) reported that heat pulse method for grapevine can be used satisfactorily with instrumentation based on low-diameter and low heat supply sensors to mark sap flow.

Heat balance technique consists of applying heat around the circumference of the stem using a heat source. The mass flow of sap is obtained through the balance of the heat that flows into and out of the heated section of the stem (Silva, 2008). It is an absolute and non-invasive method that requires no calibration procedures and involves relatively simple equipment etc. (Marin et al., 2008). However, it requires quality assessment for obtaining accurate data which is very difficult to practice under field conditions and in large plants.

The thermal dissipation method proposed by Granier, (1985) helps to determine the amount of water used by each plant for a specific period of time, through a xylematic flow monitoring. Assuming that most of the water carried through xylem is used in transpiration, it is can be quantified, indirectly, the total amount of water transpired by the plant. The thermal dissipation method to measurexylematic sap flow consists of a probe made up of two stainless steel cannulas inserted into the plant stem, with 3-cm length and 2-mm diameter, lined up vertically at a distance of approximately five inches.

Water consumption from sap flow data

The use of sap flow methods is suitable for studying water deficit because this methodology may help to quantify both transpiration reduction and water stress level reached by the plant. The sap flow, measured in the evening, is a good indicator of plant water condition in vines and it correlates well with stomatal conductance, and can be successfully used for determining in situ water consumption of plants (Pons et al., 2008; Fernandez et al., 2008a). This system is easily automated and provide satisfactory results to estimate transpiration. An irrigation automatic control system for fruit tree orchards calculates water demand from sap flow readings in the trunk of the trees at the end of each day. The system is capable of filtering and amplifying tensions of heat-pulse velocity probes to calculate sap flow data thus provides the daily amount of irrigation water for orchards according to a specific protocol for the culture (Fernandez et al., 2008b). However, field sap flow measure for the irrigation management, with the existing equipment available in the market has technological challenges of its high cost and easy availability.

e) Xylem cavitation

It is generally accepted (Steudle, 2001) that water in the xylem vessels of transpiring plants is under tension; as water deficit increases, this tension is supposed to increase to such an extent that the water columns can fracture, or 'cavitate'. Such cavitation events lead to the explosive formation of a bubble, initially containing water vapour. These cavitation events can be detected acoustically in the audio- (Milburn, 1979) or ultrasonic-frequencies (Tyree and Dixon, 1983), and the resulting embolisms may restrict water flow through the stem. Evidences indicated that the ultrasonic acoustic emissions (AEs) detected in stressed plants infer cavitation events and the AE rates can be used as an indicator of plant 'stress' (Tyree and Sperry, 1989). Measurement of AEs has proved to be a powerful tool to study hydraulic architecture in plants, however, little progress has been achieved in adapting this measure as an indicator for irrigation scheduling.

f) Stomatal conductance and thermal sensing

Changes in stomatal conductance are sensitive to developing water deficits in many plants and may be a good indicator of irrigation need in many species. In this area most efforts have been concentrated to develop practical, plant-based irrigation scheduling approaches. Stomatal conductance can be measured accurately using various diffusion porometers, but the measurements are labour-intensive and unsuitable for automation. Leaf temperature tends to increase as plants are droughted and stomata is closed (Raschke, 1960) and it led to a major effort during the period of 1970-1990 to develop thermal sensing methods, e.g. infrared thermometers for the detection of plant stress (Jackson, 1982; Jones and Leinonen, 2003; Jones, 2004). It is a sensitive measure of plant water status but is also sensitive to light and leaf-to-air water vapour concentration difference (Sehulze & Hall, 1982; Turner et al., 1984). Hence, it is difficult to use on the partly cloudy days which are common in many tropical and subtropical environments.

g) Infrared thermometry

Infrared thermometry (remote sensing) based plant water indicator approach has been considered as a reliable and non-destructive alternative to soil moisture-based methods. Infrared thermometers, which sense canopy temperatures remotely without making direct physical contact, are the fast and reliable tools which are becoming popular. Using infrared thermometers, canopy temperature can be remotely detected and the value can be used in irrigation programming and to predict crop yield. It has been reported that the crop plant water stress index (CWSI) value obtained through the use of plant surface temperature is a reliable indicator of the plant stress and by using this value for irrigation scheduling, the targeted efficiency, quality and water savings can be achieved. The crop water stress index (CWSI) derived from canopy temperature (measured using infrared thermometer) has been widely utilized for indicating plant water status and scheduling irrigation in different crops.

Irrigation scheduling based upon crop water status can be more advantageous since crops react to both the soil and aerial environment. So, plant-based scheduling of irrigation is becoming more popular. The irrigation time can be determined by detecting the water stress status of the plant. Useful information may be obtained about the water status on the basis of canopy temperature measurements. Plant surface temperature is directly related to its transpiration rate. It is assumed that as water becomes limiting, transpiration is reduced and crop temperature will be higher than air temperature because of the absorbed radiation. Plant under water stress has a tendency to close the stomata to lessen transpiration leading to an increase in leaf temperature. The leaf energy balance shows that this change in leaf temperature also depends on ambient conditions (relative humidity, wind speed, and ambient temperature) and radiation received by the canopy surface.

Canopy temperature

It can also be used as an indicator of crop water status (Jackson, 1982). With the closure of stomata with the development of water deficits, canopy temperature increases relative to air temperature. For comparisons from one day to another the variation in water vapour concentration difference on canopy conductance, and hence canopy temperature, needs to be taken into account as per the methodology suggested by Jackson (1982). Thus, canopy temperature provides a good measure of crop water status (O'Toole et al. 1984). Canopy temperature can be measured remotely by using: infrared thermometers held in hand or mounted above the crop and can be used for irrigation scheduling (Johnson,1987). Canopy temperature is sensitive to wind speed (O'Toole & Hatfield, 1983; Oosterhuis & Walker, 1987) and radiation conditions. Thus, it is difficult to use during gusting winds and partly cloudy sky inducing stomata to open and close as the quantum flux density varies.

Crop water stress index:

The CWSI represents the linear relationship between canopy–air temperature difference (Tc - Ta) and vapour pressure deficit (VPD) of air for a crop transpiring at its potential rate. CWSI is described based on relationship of two parameters i.e. Tc- Ta and AVPD (Idso et al., 1981), and the line obtained by this equation is called the lower baseline (L.L) (Taghvaeian et al., 2013):

$$(Tc - Ta)_{U.L} = a - b\,(AVPD) = a - b\,\{10 \times e^{[16.78Ta - 116.9/Ta + 237.3]} \times (1 - RH/100)\}$$

Where Tc is the canopy cover temperature (°C), Ta air temperature (°C), AVPD air vapour pressure deficit (mbar), RH relative humidity (%), a and b are the different constant coefficients for crops and fruit trees. The lower baseline is a special characteristic of each plant and represents the conditions where the plant has no limitations on root water supply, and the air vaporization rate is at its maximum (Idso et al., 1981). The upper baseline (U.L) also represents the maximum (Tc- Ta) expected. The upper baseline status is obtained using the following relation (Idso et al., 1981):

$$(Tc - Ta)_{U.L} = a + b\,(AVPG) = a + b\,\{e_s(Ta + a) - e_s(Ta + a) - e_s(Ta)\} \qquad \text{-Eq. 1}$$

$$e_s(Ta) = (0.6108 \times e^{(17.27 \times Ta/237.3 + Ta)}) \times (1000/101) \qquad \text{-Eq. 2}$$

Where AVPG is the air vapour pressure gradient (mbar) and coefficients a and b are obtained from the lower baseline (Eq. (2)). The empirical CWSI is also calculated by the following equation:

$$CWSI = (5)\,(Tc - Ta)_m - (Tc - Ta)_{L.L} / (Tc - Ta)_{U.L} - (Tc - Ta)_{L.L}$$

where $(Tc- Ta)_m$ is the difference between the canopy temperature and air temperature (pre-irrigation) at the time of measurement (°C), $(Tc- Ta)_{L.L}$ is the difference between the canopy temperature and air temperature (post-irrigation), which is obtained from the lower baseline equation. $(Tc- Ta)_{U.L}$ is a constant for the upper baseline (post-irrigation).The CWSI has been used in numerous studies on irrigation management. In the most studies, CWSI results are consistent with yield, yield varied linearly with the CWSI in eggplant, broccoli, watermelon, pepper (Senzen et al., 2019). Osroosh et al., (2015) accordingly developed a CWSI dynamic threshold (CWSI-DT) which beyond following the conventional CWSI method, added three further rules: (1) no irrigation is required as long as the CWSI shows a decreasing trend; (2) irrigation must be stopped if no observable decrease in the CWSI occurs after several successive irrigation events exceeding soil water–holding capacity; and (3) no irrigation is needed if evaporative demand is too low. Osroosh et al., (2015) reported that the proposed CWSI-DT method was able to avoid the false stress signals caused by the effect of wind, shoot growth, or other unwanted factors, and to minimize the effect caused by temporary atmospheric conditions, along with those associated with infrared thermometer installation and measurement errors. The erroneous stress signals in the early season were prevented as well.

h) Use of dendrometry in order to obtain crop water status

Dendrometry is based on the monitoring of changes in dimensions of plant organs in response to their water balance, and mostly variations in trunk or branches variations are more commonly used. However, in case variation in trunk diameter is very small, a highly sensitive apparatus is necessary (Souza, 2009) and these devices are called dendrometers. They use fixed strain transducers on a steel arm, in which the smallest fraction of arm movement can be detected in the form of electrical signals that are subsequently converted to micrometrics signals. The most commonly used parameters in this technique include maximum daily diameter amplitude of trunk, stem and branches, and the variation of maximum or minimum daily diameter over the time (Goldhamer et al., 1999; Goldhamer & Fereres, 2001). The index from the maximum trunk contraction measures is an appropriate parameter for irrigation management during the vegetative period. However, the accuracy of index adjustments depends on the phenological stage and the intensity of plant stress (Puerto et al., 2013).

In addition to scarcity of water, trunk diameter variation also depend on seasonal growth patterns, fruit burden, age and size of the plant that limit the usefulness of trunk diameter variations indices as indicators of water stress. The technique does not always provide satisfactory irrigation schedules due to temporal changes in trunk contractions of the reference used to calculate signal strength, absence of hardware and software packages (Bonet et al., 2010).

i) Zim probe: a new tool for irrigation management

Variations of leaf water potential before sunrise and at noon can be determined through a newly developed commercial probe ZIM probe, which provides information about relative changes in leaf turgor pressure (Zimmermann et al., 2008). The probe consists of a miniaturized pressure sensor integrated to a magnetized support, which is positioned on an intact piece of leaf in the plant (Zimmermann et al., 2009). The steady pressure for fixation on the leaf is applied in a way that the pressure sensors are able to detect relative changes in turgidity (Bramley et al., 2013).

Once turgor pressure is related to leaf water potential and xylem pressure, the most important driving forces for sap flow can be monitored longer (Rodriguez-Dominguez et al., 2012). Thus, multiplying the stored values determined by the probe and the sap flow, it is possible to study the transport of water over a time interval, by measuring from a single leaf, water status of the entire tree.

This probe method became an important tool in plant physiology, molecular biology, ecology and also for irrigation management evolution (Zimmermann et al., 2013). It is a robust and easy-to-use method, through which producers can receive the information about the water needs of plants by wireless telemetry, mobile network and internet, and can thus, precisely adjust both the time and amount of irrigation water to be applied. ZIM-probe may be used as an early warning system of water stress beginning and the probe leads to more appropriate form of measuring crop water demand, both in the field and in the greenhouse (Westhoff et al., 2009). The automated dendrometers and ZIM-probe are easy-to-use equipments and tools that operate on a continuous basis for the study of the water relations of trees, with great precision and high temporal resolution. The probe and the data transfer system are an accurate and robust technology, which is able to continuously monitor plant water conditions, under field conditions, throughout different irrigation managements. This real-time information is beneficial to irrigation management in commercial orchards, in which the efficient water stress control is necessary for applying controlled water deficits.

j) Relative water content (RWC)

Another method to quantify leaf water status is by measuring relative water content (RWC) of the leaf (Prakash and Singh, 2020). The RWC is a comparison of the water content of a leaf to the maximum possible water content of that leaf at its full turgor (Ihuoma and Madramootoo, 2017). The RWC is highly associated with the cell turgor and cell turgor further controls the cell expansion. Relative water content of black gram leaves was measured four times during crop growth period whereas, it was measured during four days (before and after irrigation) every other week. Two to three adult and young leaves were cut in the direction of the sunlight after measurement at the maximum stress time and were placed in plastic bags and transferred to the laboratory immediately (Khorsand et al., 2019). The RWC values were obtained by the following Equation (Barrs and Weatherley, 1962)

$$RWC = FW - DW / TW - DW$$

where FW = fresh leaf weight (g), TW= leaf weight at full turgidity (g) and DW leaf weight after drying in oven (g). The FW value was obtained after the leaves were removed from the crop. The leaves were then immersed in distilled water for four hours. After achieving equilibrium, the leaves were removed by forceps and dried gently and their weight (TW) was measured and the leaves were placed in a paper bag to dry in the oven at 70 °C for 24 h, so as to obtain their dry weight (DW) (Barrs and Weatherley, 1962; Kirkham, 2005).

k) Leaf water potential (LWP)

Plant water status is the key factor affecting the yield and quality of horticultural crops. It is crucial to maintain the optimum plant water status. If the plant water status declines beyond a certain limit (threshold level), there is a severe decline in yield and quality of vegetable crops. Hence, there is a need to determine the threshold plant water status (Jones, 1990; Prakash and Singh, 2020). Water potential is the main driving force to transport water from roots to the leaves (Robbins and Dinneny, 2015). Use of pressure chamber/bomb is a quicker way to measure the water potential in large crop tissues i.e., leaves and stems. It is assumed in this technique that water pressure within vasculum is close to the average pressure potential of the entire organ as usually the osmotic pressure of the vasculum is low. According to Stegman (1983), a pressure bomb measures the compressive or expansive potential of the vasculum. However, osmotic potential of the vascular juice is usually insignificant compared to the compressive potential, hence, the negative pressure value in the pressure chamber is usually taken as the potential of the entire leaf. The pressure bomb is made of a hollow chamber to accommodate the leaf specimen through a gasket to hold the petiole. There is also a pressure capsule which draws compressed air into the chamber. On the other hand, the same chamber is also connected to a barometer. The leaf is placed into the chamber with its petiole outside, and as the valve of the compressed air capsule opens, the pressure inside the chamber increases gradually. The leaf wrinkles (wilts) and reaches a pressure point where a drop comes out of the petiole and when the first drop is observed, the pressure is read on the machine. The leaf samples, completely exposed to sunlight, were selected from each treatment plot in the afternoon at 2-3 p.m. local time when the LWP reached its lowest.Each leaf sample was selected, cut by a sharp blade cutter and immediately put into the apparatus and the pressure in the chamber was increased by opening the gas valve. As the pressure in the chamber increased, the cut end of the leaf lamina outside the device was carefully observed using a handheld magnifying glass. The procedure was repeated for other samples and the mean LWP was obtained.

l) Automation

Automated irrigation scheduling systems is widely used in the intensive horticultural and especially in the protected cropping sector. In general, the automated systems in commonly used based on simple automated timer operation, or in some cases the signal is provided by soil moisture sensors. In timer-based operation, systems simply aim to provide excess water to runoff at intervals (e.g. flood-beds or capillary matting systems), whereas, in some cases only limited water is applied to replenish evaporative losses (often calculated from measured pan evaporation; Allen et al., 1999). High sophistication is required if the objective is to improve the overall irrigation water use efficiency or to apply an RDI system. Rest of the automated systems currently in operation base control on soil moisture sensing and this approach has the potential for greater precision and improved water use efficiency.

Applications of automated plant-based sensing are mostly in the developmental stage, as it is necessary to supplement the plant-stress sensing by additional information (such as evaporative demand). In principle, increased frequency on-demand irrigation systems a real-time control system can be envisaged where water supply is directly controlled by a feedback controller operated by the stress sensor itself, so that no information on the required irrigation amount is needed. For such an approach, it is necessary to take account of any lags in the plant physiological response used for the control signal.

m) Temperature Stress Day Method

The TSD method is based on the difference between the stressed and non-stressed T°c of a given crop (Clawson and Blad, 1982; Gardner et al., 1981a, b). Even though it is more easily affected by some environmental factors (e.g., humidity) (Clawson et al., 1989), given their simplicity, TSD indices have been applied in a number of recent studies (Taghvaeian et al., 2014; DeJonge et al., 2015). Taghvaeian et al., (2014) evaluated the simple TSD index, the degrees above non-stressed (DANS), which represented the difference between stressed and non-stressed canopy temperatures. When applied to sunflowers (*Helianthus annuus* L.), they found DANS to be strongly correlated with several crop parameters, including the fraction of intercepted photosynthetically active radiation (fIPAR), leaf area index (LAI), leaf water potential, and root growth. Accordingly, it was suggested that a simple DANS index, based solely on T° c and estimated by a simple subtraction, might be used as effectively as CWSI in monitoring of plant water status and therefore, in scheduling irrigations for sunflower in arid/semiarid regions. DeJonge et al., (2015) evaluated six canopy-temperature-based water stress indices, including three previously proposed (CWSI, DANS, and TTT), and three newly introduced: degrees above critical temperature (DACT; critical temperature is equivalent to temperature threshold defined in TTT method), integrated DANS (IDANS), and integrated DACT (IDACT). Their experiment showed that the simple indices, DANS and DACT, and their integrated surrogates generated similar representations of water status as CWSI, but with fewer parameters. Given its simplicity, the TSD method is likely to be adopted by farmers in irrigation scheduling for some crops in some regions.

n) Visual plant symptoms

The visual signs of plants are used as an index for scheduling irrigations e.g. plant wilting, drooping, curling and rolling of leaves, etc. Water stress in some crops leads to appearance of carotenoid (yellow and orange colour) and anthocyanin pigments. Shortening of internodes in sugarcane and cotton, retardation of stem elongation in grapes, leaf abscission and lack of new growth and redness in terminal growth points of almond are some of the examples of indices for visual plant symptoms for irrigation scheduling.

Soil-cum-sand mini-plot technique:

1. The principle involved in this technique is to reduce artificially the available water holding capacity of soil profile (i.e., effective root zone depth) in the mini-plot by mixing sand with it.

Indicator plants:

2. In maize, scheduling irrigation on the basis of wilting symptoms in sunflower gave the highest grain yields.

Critical growth stages:

3. The crop plants in their life cycle pass through various phases of growth, some of which are critical for water supply. The most critical stage of crop growth is the one where high degree of water stress would cause maximum loss in yield. Scheduling of irrigation on the basis of critical growth stages is simple and easy for the farmers.

Conclusion

This chapter has briefly highlighted the relative efficacy of different plant-based water stress indicators to detect and measure the water stress and also for their potential to be used in irrigation scheduling in crops. Plant-based water stress indicators have an advantage over the soil-based approaches as they can sense water stress due to the cumulative effect of low soil moisture availability and increased atmospheric water demand. Most of the water stress indicators mentioned above are responsive to water stress. They can be successfully used to detect and measure the water stress level in crop subjected to different water-deficit levels. Moreover, plant-based water stress indicators can be quite helpful in screening the drought-tolerant cultivars. However, these water stress indicators are incapable of discerning the cause of water stress (increased evaporative demand or declined soil moisture status), which makes them unsuitable for irrigation scheduling in vegetable crops grown under highly fluctuating environmental conditions. They can lead to under or over-irrigation under varying environmental conditions. Therefore, plant-based water stress indicators can be used only for locations where there are very little fluctuations in environmental conditions. Threshold values of plant-based water stress indicators for irrigation scheduling vary for crop species and genotypes (isohydric or an isohydric, drought susceptible or tolerant) as well as for varying environmental conditions. Intensive research is required to determine the threshold values for each crop species by taking into account the effect of environmental variations on existing level of water stress so that plant-based water stress indicators can be successfully implemented for irrigation scheduling in each crop species. Similarly, for precise water stress detection by plant-based methods, more research is required to determine the relative efficacy of different plant-based water stress indicators by involving a number of water stress indicators at a time for each crop species. In addition, it is important to consider the effect of varying environmental conditions on effectiveness of each water stress indicator to detect water stress precisely.

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