End Report: Seed Money Project 2023

Sustainable Cultivation of Ginger and Turmeric in Greenhouse in India

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Report WPR-1268

Referaat
Dit rapport vat de inzichten samen die zijn verkregen uit een haalbaarheidsstudie naar duurzame, hulpbronnenefficiënte teelt in Indiase kassen, met name voor de hoogwaardige gewassen gember en kurkuma. Het onderzoek is uitgevoerd als onderdeel van een Seed Money Project van de Nederlandse Topsectoren Agri & Food, Tuinbouw en Uitgangsmaterialen. De huidige status en belangrijkste uitdagingen van de beschermde teelt, met name de glastuinbouw, worden geschetst, samen met potentieel interessante richtingen voor onderzoek en investeringen door de Nederlandse glastuinbouw.

Abstract
This report summarizes the insights gained from a feasibility study on sustainable, resource-use efficient cultivation in Indian greenhouses, particularly for the high-value crops, ginger and turmeric. The study was carried out as part of a Seed Money Project by the Dutch TopSectors Agri & Food, Horticulture & Starting Materials. The current status and main challenges of protected cultivation, particularly greenhouse horticulture, are outlined along with potentially interesting directions for research and for investment by the Dutch greenhouse industry.

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Disclaimer

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Summary

This report compiles the insights gained during a feasibility study for sustainable, resource-use efficient cultivation in Indian greenhouses, particularly for the high-value crops, ginger and turmeric. The study has been funded as an International Seed Money Project by the Dutch TopSectors Agri & Food, Horticulture and Starting Materials to look for opportunities for the Dutch greenhouse industry abroad.

Protected cultivation, particularly greenhouse horticulture, can provide solutions to several issues currently affecting food production in India: climate-vulnerability – particularly heat waves and irregular monsoons, soil quality degradation through heavy-metal contamination, and food-safety issues such as high pesticide residue levels. At the same time, good optimization of growing conditions could boost yield and quality, especially of high-value crops like ginger and turmeric, which have a growing demand across the world, but face export rejections due to quality issues. The huge potential for growth of greenhouse horticulture in India offers many opportunities for the Dutch greenhouse industry to provide solutions tailored to the diverse local climates and socio-economic conditions across India. Some promising directions are related to the challenges of: (i) optimizing crop cultivation strategies and capacity-building for greenhouse management,
(ii) managing of extreme heat and high humidity through greenhouse design and technology, and
(iii) development of indigenous ecological biocontrol strategies based on indigenous species of natural predators.

Chapter 1 gives a brief overview of Seed Money Projects, the project consortium, and a summary of the main insights. Chapters 2,3,4, and 5 further elaborate on these insights: Chapter 2 focuses on general considerations applicable to greenhouses in India, whereas Chapters 3, 4 and 5 focus more on the region and case of the local problem owner – Simply Fresh farms in Hyderabad – with respect to the issues of greenhouse design and climate control, crop cultivation, and biological control, respectively. Section 6 lists the main conclusions of the study.

1 Introduction

This chapter gives a general overview of Seed Money Projects, and describes the objectives of the SMP project, the consortium supporting the project, activities carried out, insights gained from them, and the follow-up steps carried out.

1.1 SMP Overview

Seed Money Projects, funded by the Dutch top-sectors Agri & Food and Horticulture & Starting Materials, serve to initiate (act as the 'seed' for) development of international partnerships for Dutch companies and small and medium-sized enterprises (SMEs) that contribute to the *Kennis- en Innovatieagenda*/Knowledge and Innovation Agenda (KIA) missions and priorities of the top-sectors as well as the earning capacity of the Dutch companies. The main goal is to form a consortium to explore the possibilities for innovative international activities related to food security, sustainable food and ornamental systems, and innovation cooperation (R&D). Together with the consortium, the feasibility is assessed for international cooperation, development of new knowledge and/or the application of existing knowledge and innovations under other/local circumstances. On the basis of this, a new or improved consortium is formed. The study aims to act as "seed" and the outcome will preferably initiate next steps, for instance a (Top-sector PPS) research proposal with Wageningen Research or another knowledge institute and/or a Public private partnership via RVO instruments or other international donors.

1.2 Motivation for the research

Our project aimed to assess the feasibility of sustainable and resource-use efficient greenhouse cultivation in general, and of ginger and turmeric in particular, in India. The project was aligned with the KIAs: climate-proof rural and urban areas, and appreciated, healthy and safe food. The country of focus was India is due to its growing economy – leading to increasing purchasing power of its citizens and growing demand for healthier, sustainably-sourced, residue-free food. In particular, consumption of food with medicinal-value such as ginger and turmeric increased drastically during the COVID and post-COVID period not just in India, but also abroad, including the Netherlands [1], [2].

Like the majority of agricultural production in India, ginger and turmeric have predominantly been cultivated in the open-field, with only 0.2% penetration of protected cultivation [3]. Open-field grown agricultural produce in India has been under the scanner for heavy-metal contamination and high pesticide-residue levels [4]–[6], making it often unsuitable for local consumption and for exports, due to the stringent quality standards of the European Union, USA, etc. Improving the quality and safety of agricultural production, especially for fresh and medicinally in-demand crops, is imperative for local consumption for prevention of the waste created by export-rejection, globally.

Another challenge for open-field production is the increasing frequency of climate-change-induced weather extremes such as heat waves, untimely and irregular rainfall, and consequently water shortages which affect yields, food prices, and ultimately food security. India was stated to be the 7th most vulnerable country with respect to climate extremes [7], and the impact of extreme weather patterns is not just felt locally [8]–[10], but also in the countries where India exports agricultural produce [11], [12].

For ginger and turmeric in particular, the challenges of open-field cultivation include – low production/yields, dependence on rainfall, and susceptibility to diseases such as rhizome rot, leaf spot, particularly increased in case of waterlogging during monsoons [13].

Greenhouse horticulture offers solutions to many problems arising in open-field cultivation:

- better protection against weather extremes;
- control over growing conditions to improve production and quality;
- increased resource-use efficiency, such as for water and nutrients;
- soilless cultivation of crops offers automatic protection against soil-borne diseases and heavy-metal residues;
- in the controlled environment of the greenhouse, integrated pest management (IPM) techniques, including the use of biological control, can be practiced with much better control as compared to the open field.

In the course of this project, we have tried to learn more about the current scenario, scope, opportunities, and challenges of greenhouse horticulture in India. Another goal was to identify the most promising and innovative Dutch technologies to make the greenhouse production process as energy- and resource-use efficient as possible, and to look for business cases for Dutch companies to expand their business and invest in India.

1.3 SMP Consortium

As one of our goals was to identify the most relevant Dutch technologies for greenhouse climate control and crop cultivation, we aimed to include a broad range of partners in the consortium ranging from greenhouse construction and design, irrigation, automation, active and passive climate control technologies, as well as business case development.

In the process of building the consortium, we came across the Partners-in-Business (PIB) cluster HortiRoad2India [14]. This is a public-private partnership consortium active in India comprising of companies with knowledge and expertise ranging across the entire horticulture sector in the Netherlands. The cluster has been actively creating connections with Indian retailers, investors, AgTech firms, and greenhouse builders to develop new mid and high-tech greenhouses and upgrade existing greenhouse facilities to promote food security and safety with a fork-to-farm approach.

Thanks to the support and collaboration from the PIB, the consortium for the SMP largely comprises of members of the PIB cluster working on a project with a local problem owner – Simply Fresh Farms: a large-scale precision farming facility growing vine crops, herbs and nutraceuticals.

The companies that formed the SMP consortium are:

Wageningen University & Research	
Dutch Greenhouse Delta (PIB cluster leader):	Business Development and scaling plan for greenhouses
Lumiforte (PIB):	Smart coatings for shading
Ridder (PIB):	Screens, Climate control
Hoogendoorn (PIB):	Automation, greenhouse climate, water & energy management
Viscon (PIB):	Automation solutions for plant production
Meteor Systems (PIB):	Cultivation, heating and irrigation systems
Van der Hoeven Horticultural Projects (PIB):	Greenhouse design and construction
Koppert (PIB):	Biological pest control
Simply Fresh Farms (PIB):	Precision farms
Horizon11:	Business development in food
Genap BV:	Rainwater harvesting and storage
Reso-Power:	Mobile and accessible solar power solutions

Additionally, our efforts in the project were supported by the Dutch Embassy in India, especially the proposal formulation and submission.

1.4 Objectives

The objectives outlined in the SMP proposal were:

1. Providing crop cultivation and greenhouse design insights for the local problem-owner: Simply Fresh, a high-tech precision farming-focused enterprise based in Siddipet, India. The consortium will investigate the feasibility of sustainable, resource-use efficient, and high-yield greenhouse cultivation of ginger and turmeric.
2. Exploring the needs, opportunities, challenges, and feasibility of protected cultivation in low-, mid-, and high-tech greenhouse setups, and assessing the potential for technological intervention to boost yields and improve resource-use efficiency in these setups.
   Such a feasibility study would allow a few of the partners in the consortium (such as manufacturers of coatings, screens, biological pest control, etc.) to identify the opportunities and challenges in the low-, mid-, and high-tech greenhouse market for their products.
3. Establishing a business case for sustainable production of ginger and turmeric for diverse local problem owners in collaboration with Dutch companies and explore future R&D projects with public and private investments beyond the Seed Money Project.

We tried to attain these objectives through the following activities:

- **Joining the field-visit to India organized by the PIB cluster:** This involved visits to greenhouses located close to Hyderabad, as well as match-making sessions which facilitated interactions with growers, knowledge institutions, incubation centres, and entrepreneurs.
- **Independent field visits and networking:** visits to greenhouses near Pune and to the Centre of Excellence in Baramati, networking with Indian and Dutch companies beyond the PIB cluster for formulation of the PPS proposal.
- **Literature study**.

Over the course of the project, priorities were re-assessed and re-defined based on interactions and knowledge gained within the project.

1.5 Summary of Insights

Summarized below are some of the over-arching insights gained through the field visit, interactions with various stakeholders, and literature search. Some of these are further expanded on in Chapters 2,3, and 4.

- Crops like ginger and turmeric are grown widely in the open-field, and competing with the cost of open-field production could be a challenge for protected cultivation of these crops. However, protected cultivation offers considerable value with respect to the yield and quality of these crops - in the form of protection from heavy metal residues, fungal diseases, and irregular rainfall, as well as potential improvement in yield and quality due to optimized growing conditions. The growing demand for these crops world-wide due to their medicinal properties creates a larger market for high-quality produce.
- In existing Indian greenhouses, conventional greenhouse crops such as tomato, cucumbers, bell peppers, and lettuce are grown. There is also a scope for improvements in yields and quality for these crops.
  For instance, quality and yield of cherry tomatoes is affected by a variety of inter-related problems: e.g. the yield and the size of tomatoes in a truss is non-uniform due to hand pollination. However, use of natural pollinators such as bumblebees is limited by factors like need for chemical/bio-based pesticide spraying, and sub-optimal greenhouse microclimate.
  Several other crops are also affected by thrips' infestation, leaving no choice other than calendar spraying. In such a scenario, devising biological control strategies based on natural predators could solve multiple problems: enabling the use of natural pollinators in the greenhouse; consequent improvement of the quality, consistency and overall yield; reduction in pesticide residue levels; reduction of the manual labor involved in hand-pollination, as well as in separating different-sized tomatoes from a non-uniform truss, etc.

- The biggest pest-management challenge is the control of thrips, due to which chemical-pesticide spraying is often unavoidable. In general, biocontrol solutions such as bio-fungicides, bio-nematicides, and bio-stimulants are available in India and used as much as possible, but biocontrol based on natural enemies cannot be implemented on a short time scale due to legislative barriers on importing beneficial species.
- For substrate-growing, close monitoring of hygiene of the substrates as well as water streams, the fertilization status of irrigation and substrates (monitored through monthly analyses), disinfection of water in case of re-use and maintenance are highly important. In general, it would be good to have an expert have a look at all the cultivation practices to see if there are possibilities to do things more efficiently, also supported by technology. Another general remark is that maintenance is often a forgotten duty, and it is important to have a good schedule for this.
- There are a variety of different climate zones encompassed within India, such as arid desertic, tropical monsoon, humid sub-tropical, tropical wet and dry climate, etc. This fact presents different opportunities and challenges. While each zone will require separate consideration and optimization of design, strategies, and practices for protected cultivation of crops, the knowledge gained from these could be extrapolated to many different use-cases.
- The biggest microclimate-related challenges to manage in greenhouses in tropical wet and dry climates, in particular, around Hyderabad, are heat in the summer months and humidity during the monsoons. Usage and control of climate-control related equipment needs to be optimized – e.g pressure of misting/fogging systems, usage and setpoints for screens for shading (or for retractable roof), etc.
- At present, protected cultivation in India is dominated by low-tech structures such as net-houses and naturally-ventilated tunnels [15]. Despite providing basic protection from heavy rains, strong winds, hail, or sun burn, such structures cannot ensure optimal growing conditions, and the increase in production that such structures can bring is quite limited. However, such structures also require much less economic input than high-tech greenhouses, which can improve yield significantly and extend the growing season, but require really large up-front investments as well as skilled labor in order to realize the full potential of the greenhouse.

  The question of: 'which is the right level of technology for greenhouses in the Indian climate?' need not have a single answer, as there are different levels of economic investment capacities available in the country. The market for Dutch greenhouse technology can be even more widespread if solutions can be found for each of these different groups, especially for mid- and high-tech greenhouses.

  In order to do that, though, a lot of optimization is required to create the greenhouse conditions which will maximize yield for each technology level. Moreover, comparative trials of these different technology levels can generate data on the benefits obtained by raising the technology level in the protected structure, along with the entailed costs - giving growers across the economic spectrum data-backed options to choose from.
- To facilitate the transition from open-field cultivation to high-tech protected horticulture, one of the biggest challenges is capacity-building. In the beginning stages of adopting high-tech greenhouse cultivation, many different types of knowledge are needed, such as:
  - differences between cultivation practices in open-field and under protected conditions: which are the topics one can have more grip on, what are the ways to change, and what impact it could have on the cultivation;
  - general knowledge of crop growth, and identifying problems in the crop or its growth, related to climate, irrigation, fertigation or disease;
  - knowledge about and management of climate-control equipment, irrigation/hydroponic systems, and other automated technology in the greenhouse, maintenance of the systems and sensors;
  - optimizing conditions homogeneously across the large greenhouse area to maximize the growth and maintain uniformity of the quality;
  - safety practices against disease and pests.
- There are existing organizations and institutions focusing on dissemination of knowledge and skill-training, such as Centers of Excellence for Greenhouse Horticulture and for Agricultural Skills, but to a large extent, these cater to skills required for the open-field (based on the requirements of the much larger open-field cultivation sector in the country).

  While there are efforts being undertaken to demonstrate, build acceptance and trust in protected cultivation techniques and practices in some of these organizations, specialized training targeted on operating and managing mid- and high-tech greenhouses would be needed on a significantly larger scale than currently available to increase the penetration of this technology in India.

1.6 Follow up: PPS Proposal

Based on the insights described above, we formulated a PPS proposal that is summarized in the schematic in Figure 1.

Figure 1 *Schematic highlighting two main objectives of the PPS proposal for India: (I) trials to generate data on 'benefits' versus 'costs' of different technological levels of protected cultivation in the Indian climate, particularly for 'new' crops not conventionally grown in Indian greenhouses, and (II) identification, assessment, and multiplication of indigenous generalist natural predator species for common crops in Indian greenhouses.*

The project was aimed to be long-term, involving crop trials over multiple growing seasons in different locations comparing cultivation under different technology levels (open-field, low-, mid- and high-tech). The trials would not only serve to optimize growing protocols for different crops under different technology levels of crop protection, but would also generate data on the benefits and costs in each case, in order for growers to be able to make informed choices while designing and setting up protected cultivation systems.

Aside from the crop trials, another important goal was to identify, evaluate, and multiply local species of generalist predators of common pests in the major horticultural crops in collaboration with WUR and local knowledge institutions. This could have helped lay some groundwork for biological control based on indigenous natural enemies in the presence of the legislative barriers on importing beneficial species from the Netherlands.

We attempted to build a wider consortium for the PPS and approached various stakeholders as potential partners - including Indian greenhouse growers and knowledge institutions, and Dutch companies with expertise on climate computers and climate control equipment, irrigation and hydroponics, water management, seeds and starting materials, substrates, and biological control.

However, we were not able to successfully build a consortium and obtain sufficient budget required for such a long-term, large scale project as outlined above. In retrospect, the two broad goals of the planned PPS project, if broken down into smaller, focused projects with smaller time and budget requirements, might have had a greater chance of success.

However, the interest from the companies we approached during the consortium-building project indicates that India is an interesting and promising market for many Dutch horticultural companies, and the most promising business cases for future research projects, based on the needs and interests of the Indian horticulture sector are related to biological control, climate and crop management, and capacity building.

2 Greenhouse Horticulture in India: General Considerations

2.1 Climate

India can be divided into distinct climate zones (Figure 2) based on a survey initiated by the Agricultural Department of the Dutch Embassy in India, conducted by Hollandoor [15]:

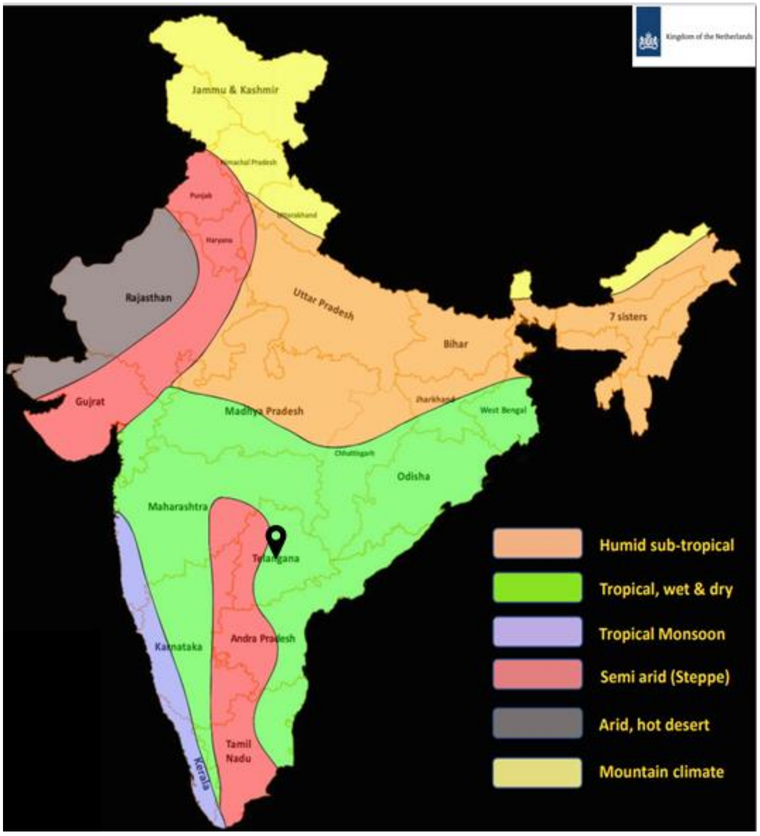

Figure 2 *Different climatic zones in India.*

While each zone has distinct climate conditions, challenges, and opportunities for protected cultivation, in the rest of this report, we focus on Hyderabad - which we visited during the PIB field visit - indicated by black pointer in the map. The climate zone here is tropical, wet and dry.

To identify the most relevant climate control technology for the Indian market from the Dutch greenhouse technology sector, we compare the local climate in Hyderabad with that of the Netherlands (plotted as monthly averages):

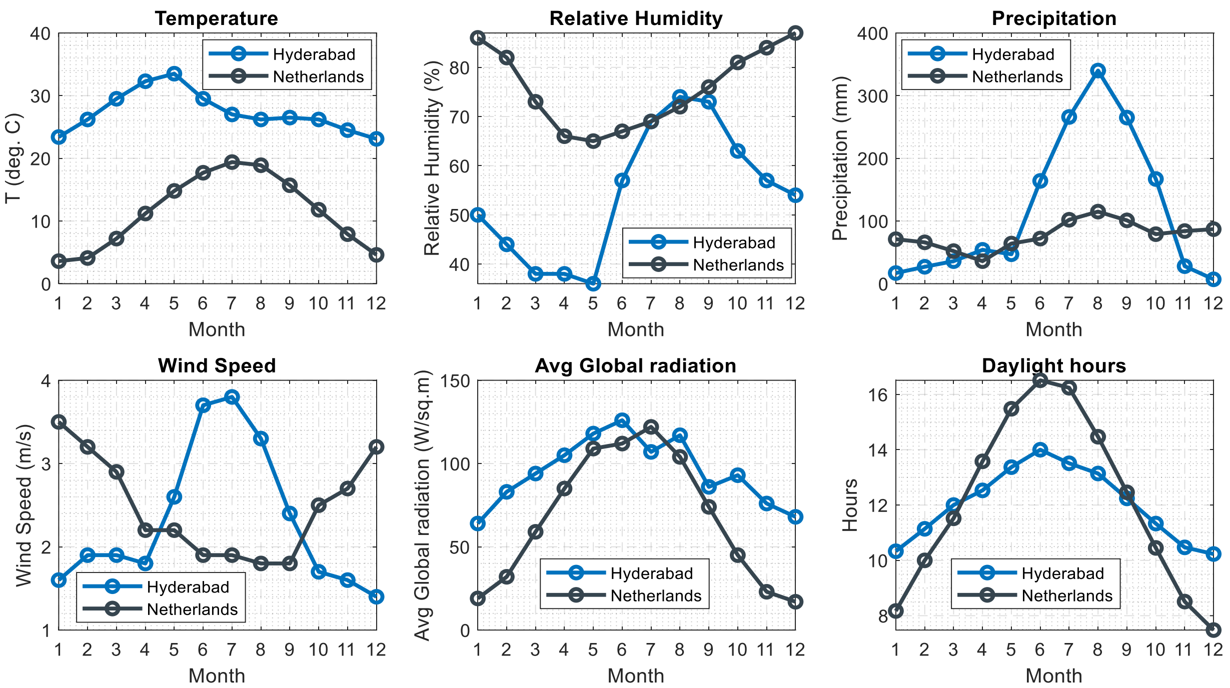

Figure 3 *Comparison of monthly averaged climate parameters: temperature, relative humidity, precipitation, wind speed, global radiation, and average day length for Hyderabad and Netherlands (data for the year 2021 measured at Hyderabad and Rotterdam airports, obtained using Meteonorm).*

Across the entire year, the average monthly temperatures are much higher for Hyderabad compared to the Netherlands. A small dip in temperatures is observed between May and September, corresponding to the monsoon, or rainy season, features of which can also be seen as peaks in the precipitation levels as well as in the relative humidity. Despite the small reduction in solar radiation during the monsoon months, across the year, the solar radiation received is either similar or significantly higher compared to the Netherlands.

In Figure 4, the monthly averaged intensity of solar radiation received plotted against the monthly averaged temperature in order to assess the most relevant climate control functions for the region. Based on this, it is clear that the most important climate control strategy for greenhouses in this region is cooling. In the monsoons, humidity management can be a challenge, and evaporative cooling methods would not work successfully in the periods with high external humidity. Heating and lighting are not particularly important across the year.

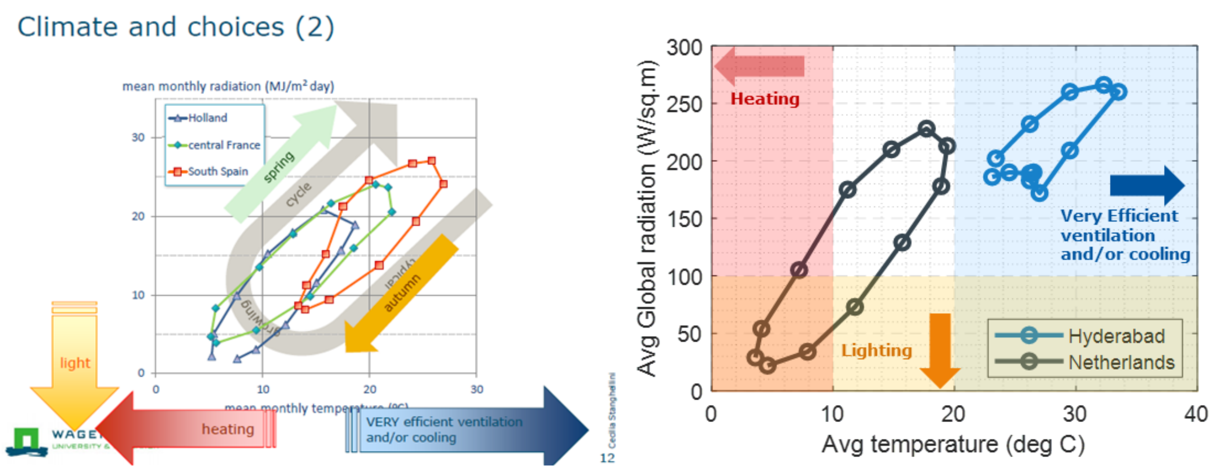

Figure 4 *Monthly averaged global radiation plotted against the monthly averaged temperature in order to identify the most relevant climate control functionalities required for protected structures: the left plot shows some examples of temperate climates; the right plot shows a comparison for Hyderabad and the Netherlands.*

2.2 Other factors

Some general considerations to determine the particular choices of the protected cultivation system in a given region are listed below, as outlined in [16]:

- Market size and regional physical and social infrastructure which determines the opportunity to sell products as well as the costs associated with transportation.
- Local climate which determines crop production and thus the need for climate conditioning and associated costs for equipment and energy. It also determines the greenhouse construction dependent of, for example, wind forces, snow and hail.
- Availability, type and costs of fuels and electric power to be used for operating and climate conditioning of the greenhouse.
- Availability and quality of water.
- Soil quality in terms of drainage, the level of the water table, risk of flooding and topography.
- Availability and cost of land, present and future urbanization of the area, the presence of (polluting) industries and zoning restrictions.
- Availability of capital.
- The availability and cost of labor as well as the level of education.
- The availability of materials, service level that determines the structures and instrumentation of the protected cultivation systems.
- Legislation in terms of food safety, residuals of chemicals, the use and emission of chemicals to soil, water and air.

Though a detailed consideration of all of the factors is beyond the scope of this feasibility study, we tried to collect information about as many of these aspects as possible in our interviews with various stakeholders and in the field visit.

Local climate:

- Heat and humidity are the major climate-related problem – their management is the key challenge in greenhouses.
- We observed several low-tech naturally ventilated, sawtooth shaped poly-tunnels apart from large-scale facilities we visited.
- The more technologically advanced facilities, including that of the local problem-owner, Simply Fresh, included Cravo-type greenhouses with retractable roofs. While a retractable roof can protect from rain, and harsh weather, the amount of regulation that can be achieved for the internal microclimate is very limited in such structures.
- There are very few high-tech glasshouses in India, and the climate management inside those structures consumes a lot of energy.

Availability of fuel and electric power:

- Overall, most of the structures we visited were low- to mid-tech (also based on the survey of protected cultivation in India [15]), and thus not energy-intensive.
- Even as electrical connectivity and availability is improving in India, there are still many regions where electric power may not be consistently available. A CEEW survey on residential electricity availability conducted in 2020 [17] found that across Indian households, the average electricity supply is 20.6 hours a day, going to more than 23 hours a day for the states Delhi, Kerala, Gujarat, and Tamil Nadu. Particularly for high-tech greenhouses, power interruptions could affect the internal microclimate control, irrigation and fertigation setups, and eventually yield, hence backup supplies would need to be kept in mind while constructing energy-intensive protected structures.
- A large portion of the electric power generated in India is generated from fossil fuels. From a sustainability point of view, optimizing energy-intensive protected structures for efficient energy-use, and sourcing electricity from renewable resources is really important.

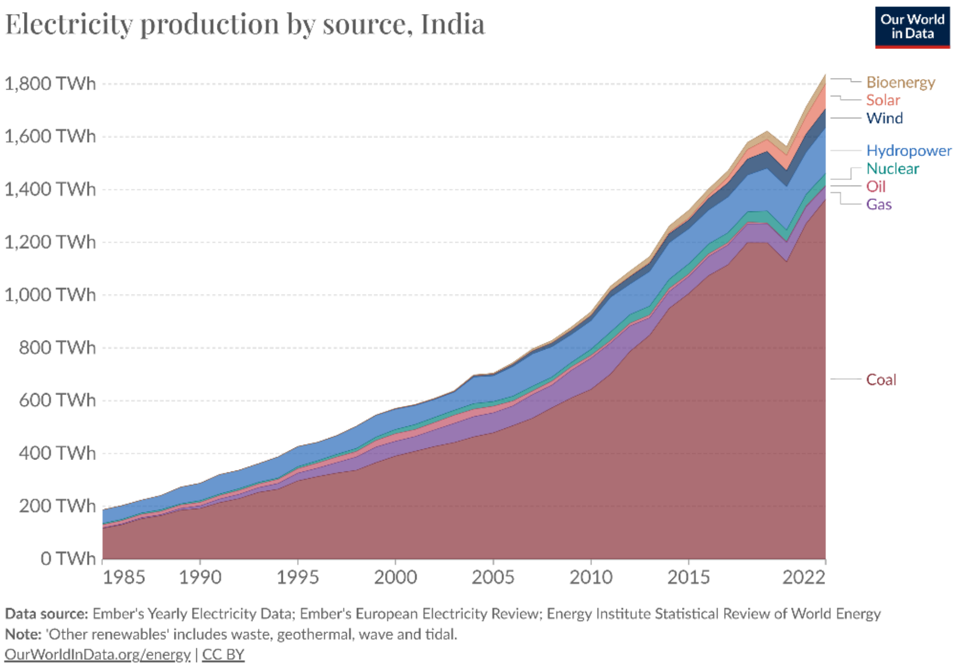

Figure 5 *Share of electricity production by different sources in India between 1985 and 2022.*

Availability of water:

- Water availability could differ in different regions of India. Based on a 2017 report [18] on open field agriculture, 42% of the country's cultivable land lies in drought-prone areas/districts, and 54% of India's net sown areas is dependent on rain, and thus consistent and sufficient water supply could pose a challenge in many parts of the country.

Availability of capital:

- There is a wide range of investment potential for horticulture across the country, including some large-scale greenhouse facilities backed by investors from other sectors, as well as high-end retail and hospitality chains. However, low-tech structures so far have the dominant share of horticulture.

Availability of labor and level of education:

- Although there is availability of labor, as the level of technology in protected structures grows, the management becomes increasingly complicated. Thus building skills and knowledge for management of greenhouse climate control equipment as well as crop management in greenhouses are highly valuable and necessary, but also lacking.
- A survey of protected cultivation in Western India [3] found that education played a key role in adoption of protected cultivation and the majority of adopters were more educated. Training programs to bridge the knowledge gap between open field and protected cultivation could increase the adoption of protected cultivation practices among a wider population of Indian growers.

Legislation:

- Legislative barriers are restricting the import of beneficial species of natural predators for common pests – this has hindered the widespread adoption of biological control via natural predators in Indian greenhouses, and also restricts the use of natural pollinators in the greenhouse due to calendar-spraying.

3 Crop Cultivation

3.1 Introduction

Protected cultivation in India currently accounts for only about 0.2% of total cultivation by area [3]. The majority of farming still relies on open fields, which are subject to seasonal climate variations and water availability. However, protected cultivation, which involves growing crops in controlled environments like greenhouses, differs significantly from open-field farming, particularly in terms of climate regulation, irrigation, and fertigation.

As the protected cultivation sector grows in India, knowledge gaps remain in the cultivation management in protected cultivation structures such as greenhouses, especially with increasing technology levels. Cultivation of conventional horticultural crops such as tomatoes, cucumbers, and bell peppers, and even herbs and nutraceuticals is being adapted and optimized by Indian growers, but additionally there is significant scope to bring several 'new' high value crops into protected settings, for instance, ginger, turmeric, black pepper and vanilla. Though these are widely grown open-field in India, protected cultivation could greatly improve their quality and safety, and thus export prospects, to meet a growing worldwide demand.

The knowledge gaps in transitioning such new crops into protected settings can be bridged by WUR expertise on bringing a wide variety of new crops inside Dutch greenhouses - such as ginger, turmeric, vanilla, black pepper, papaya, wasabi, hops, etc. Moreover, the SMP consortium members are already actively involved with several greenhouse projects in India and bring in expertise on a variety of components installed within the protected structures. A collaborative effort between knowledge institutions, industries, and growers can lead to generation of more knowledge on attaining the ideal cultivation conditions for these crops inside different types of protected structures.

3.2 Observations from field visits

Listed below are some observations regarding crop cultivation and management gathered during the PIB field visit and during interactions with growers.

3.2.1 Existing setups for tomato and bell pepper cultivation

- Problem with uniformity in fruit-set affecting the overall yield – because of hand pollination; use of natural pollinators could lead to much better and uniform sizes of tomato.
- Bell peppers: were being sprayed very frequently with pesticides – this was visible in the leaves.
- Re-use of (too) old substrates.

3.2.2 Ginger and turmeric varieties from India cultivated in Dutch greenhouses

- Yield needs to be improved and optimal growing conditions need to be identified for Indian greenhouses.
- There are variants present with high active ingredient content, for which both yield and quality may be improved under protected cultivation.
- Using the literature information from Section 3.3 there could be very interesting research possibilities on exploring to get higher production with higher ingredient content.

3.3 Literature Study and Experiments on Ginger and Turmeric

Central question: How to increase production and ingredient levels of Turmeric (and Ginger)?

Conclusion of Hossain et.al. [19] about the relative light intensity was that Curcuma longa is a partial shade-tolerant plant. Turmeric was grown in Okinawa, Japan between march and February with temperatures between 17-31 ℃, relative humidity between 60-80% - the highest production and curcumin content were realized in the range 59-73% relative light intensity. Some shading increased both production and curcumin levels [19]. Not all studies show increasing curcumin [20].

Conclusion of Flores *et al.* [21] on the effect of photoperiod, propagative material and production period on greenhouse-grown Ginger and Turmeric is the most interesting harvest of this study, and the most straightforward. Most important conclusion is that lengthening the production time and use of night interruption (to 'make' long days by using artificial illumination) can increase rhizome yield and crude fiber content with both species. The light level of night interruption used was very low (1.3 and 4.5 µmol/m^2-s). **So there is potential to overcome winter dormancy of Ginger and Turmeric.**

Conclusion of Retana-Cordero *et al.* [22] about reducing radiation strategies on open-field Ginger and Turmeric (experiments in Florida) are that reducing the amount of light with 60% shade net has no influence on the yield compared to no treatment. Based on this, moving shade screens could be used in the greenhouse order to find the optimal light levels for high production and active ingredient content. Greenhouse cultivation will not only give more grip on light, but also on temperature, humidity and water.

Another proposition in [22] is the use of Kaolin spray on the plant surface (as an alternative to shade nets). Kaolin is an organic mineral which reflects UV and IR radiation from the plant surface – reduction of heat stress by spraying could increase photosynthesis, stomatal conductance and reduce transpiration and leaf temperature, but moving screens might offer more control on the shading based on the changing light conditions, unlike kaolin spray which stays on even when the shading effect is not needed.

Interesting for growing two cycles is that it doesn't matter if the plants are flowering or not for the best production and ingredient levels [23].

More generalized information about ginger and turmeric can be found in [13]. In general harvest of turmeric is after 7-9 months after planting. Flowers occur between 109-155 days after planting depending on variety and climate conditions [13].

From the above references, and from trials carried out in Bleiswijk, in the Netherlands, some information about light conditions and day length is compiled in the table below:

Light and day length information

	Okinawa, (2004/2005)	Florida-trial (2018/2019)					Baramati, (2016)			Bleiswijk, (2019-2021)	
	Solar radiation (MJ/m²/d)	Florida day length (h)	Mean Solar Irradiance (kWh/m²/d)		DLI (mol/m2/d)		Mean Solar Irradiance (kWh/m²/d)	DLI - guessed	Day length	DLI	Day length
	Full sun		Full sun	60% shade	Full sun	60% shade	Full sun	Full sun		Use of moving screens	
Jan	7	10	3.1	2.4	22.3	8.5	4.6	33	11	2	
Feb	10						5.4	39	11.5	3	
Mar	13						6.2	>39	12	7	
Apr	16						6.8	>39	12.5	10	12
May	17						6.2	>39	13	17	15
Jun	19	13.5	5.1		39.4		4.8	35	13	20	16.5
Jul	22	13.5	5.3		38.2		4.2	30	13	20	16.5
Aug	18	13	4.9	3.2	36.8	13.7	4.3	31	12.5	19	15.5
Sep	16	12.5	4.6	3.1	31.3	11.9	3.9	28	12	14	14
Oct	14	11.5	3.8	3.0	28.6	11.1	5.0	37	11.5	9	11.5
Nov	10	11	3.2	2.7	25.2	9.6	5.0	37	11	4	
Dec	7	10.5	2.9	2.5	20.1	7.7	4.1	29	11	2	

Some insights gained from combining the different conclusions with the light levels of the trials keeping in mind the daylength are summarized below:

- **Florida-trial:** full sun is too much light (DLI of >30) and 60% shade is not enough light (DLI <14), because production is the same. There is big chance, growth and production would be better if shading could be done with more control – only use shade when it is necessary.
- In the Netherlands plants were growing from April till October with a DLI between 10-20 and that did provide a good production, but there is space for improvement.

To get insights into the ideal conditions/requirements for ginger and turmeric in Indian climate, Baramati is taken as an example region and compared with the conditions of the above trials.

Conversion to Baramati

- Outside figures of Baramati: light outside too high –> the same with Florida.
- Optimal light will probably between 15-25 mol DLI, based on light in the greenhouse and it should be possible to attain this with moving screens and coatings in balance with temperature, water and fertilization.
- *Investigating the use of night interruption lighting will be interesting. Although there is enough daily light for growing available in Baramati (or in general in many parts of India) (based on literature), a long day length might ensure that plants stay vegetative and don't go in dormancy. Research to check this assumption in the Indian climate could be useful.*

Conclusions

In order to realize high yields and quality in greenhouses:

- Different varieties of ginger and turmeric would need to be tested: the varieties which gave good yields for open-field cultivation might not always be the ones that also perform the best protected cultivation.
- Growing in a greenhouse will open opportunities to have a higher production and higher ingredient content, based on creating a better balance in light, temperature, humidity and watering strategy.
- Results from open-field research will not give the exact parameters to create an optimal balance in the greenhouse, but looking into the results carefully could give insight on good combinations of starting parameters for further trial and optimization.
- Work on creating so called response curves on light, temperature and CO_2 will help on finding the lines where parameters may balance without doing damage.

- Based on literature it should be possible to avoid dormancy, but research is needed on which light levels of artificial light are needed to avoid dormancy. At the first instance, a trial could be created with night interruption using low light levels (4.5 $\mu mol/m^2$-s) to extend day length to 16 hours.

Extra information:
Greenhouses – small trials, Filip

Cultivation in the Netherlands at WUR

- Big pots of so-called librabakken (librabakken are too low, plants fell out).
- Substrate: peat, cocopeat, perlite (perlite is clean, no interaction with fertilizers).
- Temperature between 18-30 °C.
- Humidity if possible between 60-85%.
- Cultivation between April and October.
- Production is estimated to be about 2.5 kg per pot or librabak (about 1.5 kg/m2) – however this was realized under suboptimal conditions, where the crops were grown on one side of the greenhouse as a first trial.
- It is crucial to start with a disease-free material – there are possibilities to get plantlets grown using tissue-culture (the quality is not known yet, trials are ongoing). The best varieties could also be put in tissue culture to get disease-free materials.
- Use of a clean substrate is recommended – plant can need a lot of water and fertilization.
- Drippers can be used which are pressure compensated for better distribution of the water and fertilization.
- A (moving) sun screen should be used for more to regulate high temperatures than radiation levels – **measurement of light on the crop level in the greenhouse is essential** (the use of lux as the measurement unit for PAR intensity should be avoided, see [24]).
- Fogging could be needed at daytime to control temperature and humidity.
- CO_2 with sun is a must.

Indoor facility (Filip)
- Steering on 250 micromol for 12 hours (DLI of 10.8 $mol/m^2/day$) – not optimal yet, water and fertilization should be optimized.

4 Greenhouse Design

4.1 Introduction

Although climate is one of the most important considerations in determining greenhouse design, other factors such as resource availability and market conditions also play a huge role in the practical implementation of the design. The adaptive greenhouse design approach [16] allows for the simulation of greenhouse microclimate and resource use of the designed protected structures taking inputs such as local climate, resource availability and market conditions: this is based on the combination of a greenhouse climate model, KasPro [25], a tomato crop model by Vanthoor [26], and an economic model. This model has been successfully employed by WUR for decision-support on protected cultivation structure design in different regions such as Jordan [27], Turkey [28], Norway [29], and even tropical countries locations in Indonesia [30], and Taiwan [31].

Although applying the adaptive greenhouse model is beyond the scope of this project, just by looking at the climate, some possibilities for the required climate-management strategies can already be narrowed down.

4.2 Management of heat and humidity

- Ideal conditions for ginger and turmeric growth: Average daily temperature between 18 – 30°C; average relative humidity between 60 – 85% (based on Section 3.3 – but additional research can be done on light/temp interaction in combination with daylength to stay away from resting period).
- Ideal conditions for tomato growth: Average daily temperature between 18 – 22°C; average relative humidity between 67-92%.

Figure 6 plots the daily minimum and maximum (solid grey lines) and daily mean (solid black line) temperature and humidity of Hyderabad (smoothed using a moving average of a 7-day window), with the crop thresholds marked as dashed lines. Note that the air inside the greenhouse will be warmer than the outside air especially with high solar radiation intensities, as the greenhouse acts as a solar collector.

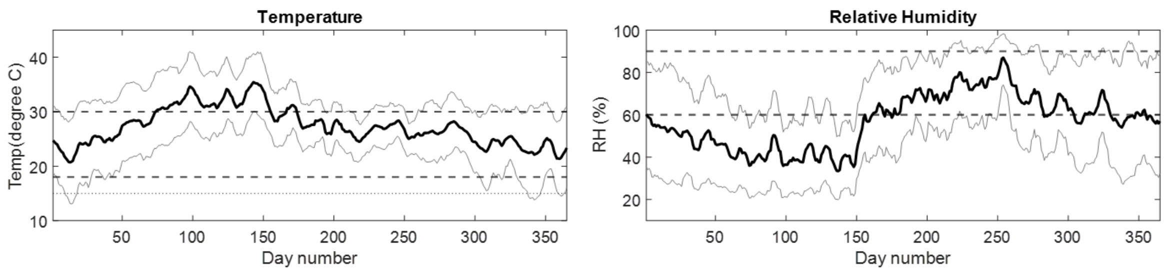

Figure 6 *Plots of daily minimum and maximum (grey curves) and daily mean (black curves) temperatures (left plot) and relative humidity (right plot) for Hyderabad for the year 2021.*

These plots re-iterate on the critical need for cooling during the summer months, particularly from the beginning of March until the end of May, when not just the maximum temperatures, but also the mean daily temperatures exceed 30°C.

From the beginning of June until the end of September, the outside humidity also increases, with the daily average exceeding 60% due to the monsoon. In this period, not only will the greenhouse humidity have to be managed, but also evaporative cooling strategies will not work very well.

The management of heat in the summer and of humidity in the monsoon can be achieved by different ways based on the technology employed (which in turn will depend on the different factors such as resource availability and market conditions).

Some strategies for heat management across various technology levels are discussed below with their advantages and limitations:

Natural ventilation:
Warm greenhouse air is exchanged with outside air through roof/side vents without significant energy expenditure – this can be done either through a fixed ventilation opening in the greenhouse structure (as in the case of sawtooth naturally ventilated tunnels), or through ventilation windows which can be open and shut, either manually, or automatically, based on a temperature set-point. However, constant air exchange with the outside, such as for permanently open vents, leads to very limited control against temperature variations over the day and over seasons.

Ventilation capacity increases with increasing the size of the ventilation opening (making larger roof vents, having side-wall vents). Vent openings should also be covered with insect netting to prevent the entry of pests in regions with high pest pressure – a smaller mesh size, which can prevent entry of more pests, will also reduce the ventilation capacity.

Ventilation capacity also depends on the direction of the wind with respect to vents and on wind speed: buoyancy effects dominate the air exchange for wind speeds below 2 m/s, and wind dominates air exchange at speeds above 2m/s [30], [32] (for instance, between April and October in the case of Hyderabad, based on Figure 3). Good ventilation also ensures input of CO_2 inside the greenhouse from the outside air, in the absence of CO_2 dosing. In the case of Simply Fresh, due to the retractable roof and side vents, the ventilation area is not limiting the ventilation capacity at all.

However, the cooling potential of natural ventilation reaches it limits when the outside air has comparable temperature as the greenhouse air, or when the outside temperatures are much higher than the desired greenhouse temperatures (e.g. between March and May in Hyderabad).

Evaporative cooling (pad-and-fan greenhouses and fogging):
These methods rely on the evaporation of water vapor present in air which is either passed through pads cooled with flowing water (in a pad-and-fan system) or sprayed at high pressure as droplets through very fine nozzles (in a fogging system) – the evaporation of water results in cooling (and humidification) of the greenhouse air. In pad-and-fad systems, the air is circulated through the greenhouse area via fans (there is no natural ventilation), whereas in fogging systems, nozzles are distributed across the greenhouse area to cool a large volume of air.

One benefit of fogging over pad-and-fan cooling is the comparative ease of retrofitting in existing greenhouses compared to pad and fan systems. Also, the cooling effect of fogging is more uniformly distributed over the greenhouse area compared to the pad-and-fan system, and the energy use is also lower for fogging. Both systems require sufficient water availability, good water quality, and maintenance – particularly fogging systems need to have especially clean water to avoid clogging the opening of the fine nozzles by particulate matter or calcium deposits.

Evaporative cooling can lower the greenhouse air temperature by a few degrees – but only when outside humidity is low. The drier the air, the bigger the cooling effect. As the humidity of the outside air increases, the potential for evaporation, and thus cooling decreases. Though the potential for evaporative cooling will be low for Hyderabad between July-October, the mean temperatures are also relatively lower. However, fogging as a way of cooling could be viable between March and May.

Shading coatings and shade screens:
Coatings and screens can reduce the transmission of sunlight through the greenhouse when employed – these methods can reduce the solar heat load on the greenhouse air and crops.

Shade coatings can be applied over the warmest months and washed off in cooler months. In the case of Hyderabad, coatings will likely be washed off in the monsoon months. But in greenhouses with retractable roofs, whitewashing is not a feasible solution.

Alternatively, shading screens can be used in the greenhouse internally or externally. The incident solar radiation determines the heat load, and also the required reduction in light transmission to maintain the greenhouse temperatures to optimal levels. Screens can be deployed or withdrawn based on the incident radiation levels. For instance, a greenhouse simulation study for Jordan [27] used the following strategy for a simulated shading screen (40% aluminized, 60% open):

	Screen closing	**Outside radiation (W/m^2)**	**Comments**
April - July	60 – 75%	500 - 650	Screens close in steps, fully closed only at high radiation thresholds
	100%	> 800	
July – Sept	100%	>500	For the hottest months, screens close fully at lower radiation threshold
Sept - Nov	100%	> 1000	Screens close fully only at a extremely high radiation threshold, allowing more solar input into the greenhouse
Throughout (at night)		If T < 15°C	To avoid radiation of heat from the greenhouse to the outside air

Although mobile screens may account for changes in radiation levels over the day and the growing season, unlike coatings, the potential to utilize the additional radiation could be limited if the greenhouse temperatures are too high, as seen in Jordan valley [27]. It was seen that lower wind velocities and internal shading screens reduced the ventilation capacity of the greenhouse, leading to higher temperatures, whereas whitewash – which did not lower the ventilation capacity – was more helpful. Thus the choice between whitewash and screens for cooling, as well as determination of the screen setpoints, would have to be made based on the external weather conditions, the greenhouse construction, and through trials and/or simulations, such as described in [33]. External shade screens, which do not reduce the ventilation capacity as much, could also be an option to lower heat loads, but they have other drawbacks (wind resistance, collection of dust).

Active cooling:
Despite a high energy consumption, active cooling systems – consisting of a cooling energy source (e.g., chillers) and a fluid-moving device (e.g., fan, pump, or circulation system) to deliver cooling to the greenhouse – will allow for the highest control over greenhouse cooling. This is only efficient in semi-closed or closed systems, where the desired level of cooling can be attained independent of any external conditions. Active cooling systems could be powered using sustainable technologies such as heat pumps, and with renewable energy supply. The initial investment could be quite steep, especially for the large volume of commercial greenhouses, however, with skilled management and operation and knowledge of optimal growing conditions, high yields can be obtained.

Considering humidity management, the passive approach of natural ventilation will not work well in months with high outside humidity (June-September). Greenhouses are often heated to higher temperatures to lower the humidity, but this is not the best option when mean temperatures are already close to the upper threshold of acceptable temperature. In the monsoon months, active strategies of dehumidification might need to be pursued, such as by using a desiccant, condensation on a cold surface, or a heat-pump dehumidifier [34], [35].

Some other technological interventions to improve the crop productivity, crop quality/safety or sustainability are:
- **Soil-less cultivation (substrate growing or hydroponics)** to prevent heavy metal contamination and improve water-use efficiency: this is already a common practice in large-scale Indian greenhouses. Recirculation of the irrigation drain water and rainwater harvesting can greatly improve the water-use efficiency, but utmost care must be taken to ensure the quality and purity of the recirculated water.
- **Heating/use of energy screens** – although this will not improve the crop quality drastically in Hyderabad, as the average outside temperature is never going below 18°C, there are a few days in December and January when the lowest temperatures dip below 15°C. On such days, better retention of heat in the greenhouse could reduce the chance of condensation and related diseases on the crop. Based on how low the night-time temperature could go, this could be done with heating based on a solar thermal collector system, or by closing shade screens in the night-time [36].

There is scope in Dutch greenhouse industry to supply many of the above-mentioned technologies to Indian growers.

4.3 General insights: Greenhouse design and technology levels

The highest level of technology, such as semi-closed greenhouses, will always attain the highest yield (caveat: significant knowledge and skill is required to get the most out of the setup) – and the internal climate can be completely made independent from the external climate (provided that energy is consistently and abundantly available to maintain the desired conditions). However, these systems are affordable only by the biggest investors. Moreover, in order to generate faster returns on investment, the market might be restricted to exports or very high-end local markets.

On the other hand, the high (and increasing) summer temperatures and monsoon humidity seen in Hyderabad (and other parts of India) make it hard to achieve optimal growing conditions in passive greenhouses without any kind of climate regulation.

However, considerable increases in productivity could also be achieved by mid-tech greenhouses at a lower economic and energy costs.

In the first place, the terminology – low-, mid- and high greenhouses – has been found to be ambiguous in terms of how it could be interpreted in different ways [37], possibly by different stakeholders in the greenhouse industry. Some examples of these different interpretations, seen in the case of Mexico, were:
- in terms of the level of control (passive/semi-active/active);
- in terms of installation costs, in terms of construction (net/plastic/glass); or
- even in terms of the most suitable climate (protective structures for "tropical climate" - protection only against hail, insects, wind/
  for "temperate climate" – additional protection against rain, moderate temperature differences/
  for "any climate" - more robust greenhouse structure with automation, heating/cooling, etc.).

Based on these interpretations, there might be differences among users in the willingness to adopt some of these technologies.

Based on which definition is selected, a mid-tech greenhouse tailored for the most relevant functionalities (using technology like screens, coatings, irrigation and fertigation setups, etc.) might still achieve comparable production to a high-tech semi-closed greenhouse (provided the cultivation is managed well).

Focusing on the mid-to-high-tech spectrum could widen the market for Dutch companies by including growers that do not upfront have the capital required to construct high-tech greenhouses, but can re-invest any gained profits to slowly "upgrade" to higher technology levels to eventually reach highly precise cultivation.

The gains from upgrading technology for different functionalities could be different in the diverse climatic regions, based on the most dominant challenges of those regions – for instance the reduction in heavy metal residues upon switching to soilless media can already drastically improve quality in regions with heavily contaminated soil but more favorable climate; moving to drip irrigation, water storage and recirculation can bring considerable gains to water-scarce, rain-fed regions, etc.

Some other advantages of mid-tech structures are: lesser initial requirements on the skill/knowledge, relatively greater room for mistakes due to smaller capital investments, and access to less high-end markets.

However, accurately quantifying and comparing the resulting increase in production or quality can be brought about by mid-tech or high-tech greenhouses can only come about through conducting controlled and comparative trials in the Indian climate.

From the sustainability point of view as well, having numbers on the energy-use would be very useful. For instance: glass-houses are made of the more sustainable, long-lasting and easy-to-clean glass, but the high retention of glass for thermal radiation in the warm Indian climate might consume enormous amounts of fossil-generated electricity to maintain optimal growing conditions. On the other hand, plastic greenhouses, while consuming less energy would generate a huge amount of plastic waste every 3-5 years, which, if not recycled or carefully disposed, or worse, incinerated, could worsen the already existing situation of plastic pollution, as resulting air, water, and soil pollution.

For systems as complex as greenhouses, a broader picture of their impact needs to be explored, and the inputs (materials, costs, energy) and benefits (yield, quality, safety) need to be quantitatively and qualitatively weighed for different types of protected structures. Multi-factorial modelling approaches and comparative trials are required for more conclusive answers.

As a general conclusion however, exploring the spectrum of designs between mid- and high-tech greenhouses, tailored to local climate and socio-economic conditions would ensure a widespread impact of the Dutch greenhouse industry in India.

5 Biological Control[1]

5.1 Introduction

Better protection of crops against the influx of pests is often seen as one of the benefits of greenhouse horticulture compared to outdoor crop cultivation. However, greenhouse crops in all parts of the world are under pressure of infestations by a wide range of pests and diseases [38], [39]. Even in greenhouses with all kinds of physical barriers and strict hygiene measures, several pests and pathogens will somehow eventually enter. A more important benefit of greenhouses is that arthropod biological control agents (BCAs) that are introduced as part of an Integrated Pest Management (IPM) approach have a much better chance of establishing compared to outdoor conditions. In the protected environment of the greenhouse, their tendency to disperse away from the release site is lower, and in climate-controlled greenhouses they are better protected against adverse climatic conditions. Many important arthropod pests are extremely polyphagous and infest almost every crop around the world, like some species of thrips, aphids, spider mites, whiteflies and mealybugs. Biological pest control by arthropod natural enemies is nowadays widely applied in many countries in the greenhouse horticulture [40].

In the beginning, biological control was very much focused on specialist natural enemies, like the parasitoid Encarisa formosa and the predatory mite Phytoseiulus persimilis, but in addition to specialist natural enemies, generalist predators also became more popular because of their ability to control multiple pest species and to establish populations in absence the pest [41]. Important generalist predators are predatory mites of the family Phytoseiidae and generalist predatory bugs belonging to the families Anthocoridae and Miridae. The increased use of such generalist predators has gone hand in hand with the development and application methods of alternative food sources, allowing for the introduction and population development of these generalist predators in the crop before the pest arrives ('standing army approach') [42], [43]. In general, control strategies have evolved from 'prophylactic calendar spraying' to the restriction in the use of pesticides based on the monitoring of pest and disease damage- and action thresholds ('threshold-based pesticide application') towards (ecologically-based) IPM that incorporates multiple non-chemical methods and allows for the use of compatible pesticides only as a last resort. The transition towards ecologically-based IPM has been most successful in fruit vegetables, such as tomatoes, cucumbers and peppers, as these crops have sufficient long crop-cycles for populations of natural enemies of arthropod pests to build up and can sustain relatively high levels of leaf damage without economic consequences.

The products that are available are mainly based on microorganisms such as bacterial and fungal antagonists against diseases and entomopathogenic fungi against some pests. One of the reasons is that the application of such microbials is more easily adopted by growers that are used to spray. However, the current package of microbials is not suitable to control the whole range of pests and diseases and additional BCAs are needed to develop robust and effective biological control programs.

5.2 Challenges and possibilities for follow-up research

In India, fundamental research on biological control is already in motion with publications surveying some invasive pests and potential natural enemies [44]–[48]. However, reports on experimental trials are fewer, and mostly target pests in open field cultivations [46], [49], where their potential is reported to be further limited by secondary parasitoids [49].

[1] With inputs and text from Prof.dr. Gerben J Messelink (WUR).

Thus, a major knowledge gap in the Indian context is implementation of biological control based on natural predators within protected environments, where their efficacy can be highly enhanced. Other challenges that have been pinpointed [50] are development of protocols for mass production, and commercialization of natural predators. Although companies with commercial biocontrol products such as Koppert have a presence in India, the import of beneficial predator species is hindered by legislative and policy barriers.

Exploration and evaluation of indigenous species of natural predators could help to overcome these barriers, though considerable research and optimization will be needed before commercialization. Adding indigenous generalist predators that perform well under the local Indian climatic conditions to the package of BCAs would be a major step forward in biological control. Generalist predatory mites and predatory bugs are in Europe the most important natural enemies that form the basis of successful biological control strategies [41]. Thus identification and evaluation of indigenous *generalist* predator species that can be used for biological pest control in greenhouse vegetable crops under Indian climatic conditions would be valuable for a broader spectrum of pest management. Some possibilities can be: generalist phytoseiid predatory mites for the control of thrips and whiteflies in pepper, cucumber and strawberry, anthocorid predatory bugs for the control of thrips, spider mites, whiteflies and aphids in pepper, strawberry and cucumber, and mirid predatory bugs for the control of whiteflies, aphids, spider mites, caterpillars and thrips in more hairy plants like tomato and eggplant.

Before commercialization efforts, several steps will be required at the laboratory scale, such as:
- collection and identification of indigenous natural predator species;
- evaluation of predation rates and potential for biological control across a variety of temperature ranges;
- development of rearing protocols;
- assessment of alternative/supplemental food sources to support the predator population in crops; and
- eventually cage and greenhouse trials.

Moreover, due to the limitations in the exchange of predator species imposed by the associated legislations, such research would be easiest to carry out in collaboration with Indian knowledge institutions. This could be facilitated via exchange programs and joint/sandwich PhD structures for Indian entomology students – where part of the training and research could be carried out in knowledge institutions like WUR in the Netherlands, and part of it could be implemented in Indian laboratories and knowledge institutions. This would also facilitate knowledge transfer in a more long-term sustainable manner.

In India, the National Bureau for Agricultural Insect Resources (NBAIR) has carried out extensive research on identifying natural predators for several crops, and has developed protocols for commercialization of certain species [51]. Collaboration between such knowledge institutes and Dutch knowledge institutes/companies could be carried out, possibly aided by funding instruments such as the Prime Minister’s Research Fellowship, or GroenPact NL.

Apart from biological control based on natural predators, there are companies offering bio-based solutions such as biostimulants, bioweedicides, bionematicides, etc., which could complement natural predators to devise holistic bio-based IPM practices, reducing the need for chemical pesticides.

6 Conclusions

The insights gained from various activities as part of the feasibility study "Sustainable Cultivation of Ginger and Turmeric in Greenhouses in India" are detailed in the above chapters. To summarize briefly:

- There is an increasing need for protected cultivation in India – as open-field agriculture is suffering from growing instances of climate-changed induced extreme weather events, soil degradation, and food safety issues due to heavy pesticide use. The consistency and safety of food production needs to be improved for local consumption as well as to prevent rejection of international exports.
- Due to a diversity of socio-economic capacities present across India, a spectrum of solutions from mid- to high-tech protected structures can offer value to a variety of growers, and opportunities for the Dutch greenhouse industry.
- For high-value crops like ginger and turmeric, there are indigenous variants available with high active ingredient content. Protected cultivation, if optimized, could potentially lead to higher yields and improved quality and safety.
- For the more conventional greenhouse crops in India, there is room for optimization, particularly with the introduction of biological control, and consequently natural predators. Several inter-related problems could be solved simultaneously in optimizing growing strategies in protected settings.
- While Dutch technology can contribute to various functions in the greenhouse, such as soilless or hydroponic growing, irrigation and fertigation, the most challenging issues to solve are:
  - heat and humidity management;
  - adapting and optimizing of growing conditions from the open-field to inside protected structures; and
  - the problem of pests, particularly thrips.

  The solutions can come in the form of various climate control (particularly cooling/dehumidification) technologies, ranging from passive to active control, trials, demonstrations, and capacity-building in greenhouse cultivation and management practices, and development of chemical- and calendar-spraying free ways of biological control, such as using natural enemies.
- Due to the diverse challenges of the different climatic zones, some technologies might be more promising compared to others – e.g. water recirculation in water-scarce arid regions, dehumidification in tropical monsoon climatic regions, etc.
- Whereas various climate-control technologies and greenhouse designs could be adapted more easily, with some optimization for the Indian climate, the development of biological control faces more legislative obstacles currently, and might have to be developed from the ground up, in collaboration with Indian knowledge institutions.

References

[1] "COVID-19 impact: Indian spices rise in demand for immunity properties, exports up 34% in June - BusinessToday." Accessed: Nov. 24, 2023. [Online]. Available: https://www.businesstoday.in/latest/economy-politics/story/covid19-impact-indian-spices-in-demand-for-immunity-properties-exports-rise-34-percent-in-june-267498-2020-07-18.

[2] "The European market potential for curcuma longa (turmeric) | CBI." Accessed: Nov. 23, 2023. [Online]. Available: https://www.cbi.eu/market-information/spices-herbs/curcuma/market-potential.

[3] P. Pachiyappan *et al.*, "Protected Cultivation of Horticultural Crops as a Livelihood Opportunity in Western India: An Economic Assessment," *Sustainability 2022, Vol. 14, Page 7430*, vol. 14, no. 12, p. 7430, Jun. 2022, doi: 10.3390/SU14127430.

[4] V. Kumar *et al.*, "Pollution assessment of heavy metals in soils of India and ecological risk assessment: A state-of-the-art," 2018, doi: 10.1016/j.chemosphere.2018.10.066.

[5] G. Singh, N. Patel, T. Jindal, and M. R. Ranjan, "Heavy Metal Contamination in Soils and Crops Irrigated by Kali River in Uttar Pradesh, India," *Bull Environ Contam Toxicol*, vol. 107, no. 5, pp. 931–937, Nov. 2021, doi: 10.1007/s00128-021-03349-7.

[6] "Research flags heavy metal contamination in vegetables across Bengaluru." Accessed: Nov. 24, 2023. [Online]. Available: https://www.deccanherald.com/india/karnataka/bengaluru/research-flags-heavy-metal-contamination-in-vegetables-across-bengaluru-2740180.

[7] D. Eckstein, V. Kuenzel, and L. Schaefer, "GLOBAL CLIMATE RISK INDEX 2021," 2021. Accessed: Nov. 24, 2023. [Online]. Available: https://www.germanwatch.org/sites/default/files/Global%20Climate%20Risk%20Index%202021_2.pdf.

[8] "Vegetable price hike explained: How climate change, global warming is fueling food inflation in India?" Accessed: Nov. 24, 2023. [Online]. Available: https://www.dnaindia.com/explainer/report-vegetable-price-hike-explained-how-climate-change-global-warming-is-fueling-food-inflation-in-india-3057643.

[9] "What's driving food prices in new normal climate?" Accessed: Nov. 24, 2023. [Online]. Available: https://www.downtoearth.org.in/blog/climate-change/what-s-driving-food-prices-in-new-normal-climate--91302.

[10] "For Second Year in Succession, Indian Agriculture Battles Climate Change." Accessed: Nov. 24, 2023. [Online]. Available: https://thewire.in/agriculture/for-second-year-in-succession-indian-agriculture-battles-climate-change.

[11] "Why India's soaring food inflation is a global problem - BBC News." Accessed: Nov. 24, 2023. [Online]. Available: https://www.bbc.com/news/world-asia-india-66655642.

[12] "India's surging food prices are a problem not just for India." Accessed: Nov. 24, 2023. [Online]. Available: https://www.economist.com/graphic-detail/2023/08/28/indias-surging-food-prices-are-a-problem-not-just-for-india.

[13] K. P. Prabhakaran Nair, *The Agronomy and Economy of Turmeric and Ginger: The Invaluable Medicinal Spice Crops*. Elsevier Inc., 2013. Accessed: Nov. 24, 2023. [Online]. Available: http://www.sciencedirect.com:5070/book/9780123948014/the-agronomy-and-economy-of-turmeric-and-ginger.

[14] "HortiRoad2India." Accessed: Nov. 23, 2023. [Online]. Available: https://www.hortiroad2india.com/.

[15] "Indian greenhouse farming - which regions to focus ? | Nieuwsbericht | Agroberichten Buitenland." Accessed: Nov. 24, 2023. [Online]. Available: https://www.agroberichtenbuitenland.nl/actueel/nieuws/2022/09/05/india-greenhouse-farming-trend.

[16] S. Hemming, E. van Henten, B. van 't Ooster, B. Vanthoor, and S. Bakker, "Systematic design of greenhouse crop production systems," *INCOSE International Symposium*, vol. 18, no. 1, pp. 1340–1354, Jun. 2008, doi: 10.1002/j.2334-5837.2008.tb00882.x.

[17] S. Agrawal, S. Mani, A. Jain, and K. Ganesan, "State of Electricity Access in India Insights from the India Residential Energy Survey (IRES) 2020".

[18] "Water and Agriculture in India", Accessed: Nov. 24, 2023. [Online]. Available: http://www.yourarticlelibrary.com/essay/essay-on-water-scarcity-in-india-1113-words/20871/.

[19] M. A. Hossain, H. Akamine, Y. Ishimine, R. Teruya, Y. Aniya, and K. Yamawaki, "Effects of relative light intensity on the growth, yield and curcumin content of turmeric (Curcuma longa L.) in Okinawa, Japan," *Plant Prod Sci*, vol. 12, no. 1, pp. 29–36, 2009, doi: 10.1626/PPS.12.29.

[20] A. B. Sharangi, M. Pavan Gowda, and S. Das, "Responses of turmeric to light intensities and nutrients in a forest ecosystem: Retrospective insight," *Trees, Forests and People*, vol. 7, p. 100208, Mar. 2022, doi: 10.1016/J.TFP.2022.100208.

[21] S. Flores, M. Retana-Cordero, P. R. Fisher, R. Freyre, and C. Gómez, "Effect of Photoperiod, Propagative Material, and Production Period on Greenhouse-grown Ginger and Turmeric Plants," *HortScience*, vol. 56, no. 12, pp. 1476–1485, Dec. 2021, doi: 10.21273/HORTSCI16025-21.

[22] M. Retana-Cordero, S. Flores, R. Freyre, and C. Gómez, "Strategies to Reduce Radiation Stress in Open-Field Ginger and Turmeric Production," *Agronomy 2022, Vol. 12, Page 1910*, vol. 12, no. 8, p. 1910, Aug. 2022, doi: 10.3390/AGRONOMY12081910.

[23] K. Kandiannan, M. Anandaraj, U. Parthasarathy, C. K. Thankamani, and T. J. Zachariah, "Study on yield and quality of flowered and non-flowered turmeric (Curcuma longa L.) plants Dry rhizome Dry recovery Curcumin Turmeric plants yield (g plant-1) (%) (mean of content (%)," *Turmeric Journal of Plantation Crops*, vol. 43, no. 1, pp. 71–73, 2015.

[24] E. Nederhof and L. Marcelis, "Calculating Light & Lighting," 2010. Accessed: Dec. 20, 2023. [Online]. Available: https://edepot.wur.nl/156931.

[25] H. F. De Zwart, "Analyzing energy-saving options in greenhouse cultivation using a simulation model," Wageningen University and Research, 1996. Accessed: Nov. 30, 2023. [Online]. Available: https://www.proquest.com/openview/832e5eb2a4b39935b88187d437e1a24e/1?pq-origsite=gscholar&cbl=18750&diss=y.

[26] B. H. E. Vanthoor, "A Model-Based Greenhouse Design Method - ProQuest," Wageningen University and Research, 2011. Accessed: Nov. 30, 2023. [Online]. Available: https://www.proquest.com/openview/a872ac30862c6ed05c880617b050c888/1?pq-origsite=gscholar&cbl=2026366&diss=y.

[27] E. J. Baeza Romero, E. A. van Os, C. van der Salm, I. Tsafaras, and C. Blok, "Exploring the boundaries of the passive greenhouse in Jordan: a modelling approach," *Acta Hortic*, no. 1268, pp. 43–50, Jan. 2020, doi: 10.17660/ActaHortic.2020.1268.6.

[28] Y. Tuzel, H. F. de Zwart, A. Sapounas, S. Hemming, and C. Stanghellini, "Improvement of greenhouse climate control in Mediterranean conditions: a case study from Turkey," *Acta Hortic*, vol. 1170, no. 1170, pp. 889–896, Jul. 2017, doi: 10.17660/ActaHortic.2017.1170.114.

[29] M. Naseer, T. Persson, I. Righini, C. Stanghellini, H. Maessen, and M. J. Verheul, "Bio-economic evaluation of greenhouse designs for seasonal tomato production in Norway," *Biosyst Eng*, vol. 212, pp. 413–430, Dec. 2021, doi: 10.1016/J.BIOSYSTEMSENG.2021.11.005.

[30] S. Hemming, D. Waaijenberg, J. B. Campen, G. P. A. Bot, and Impron, "Development of a Greenhouse system for tropical lowland in Indonesia," *Acta Hortic*, no. 710, pp. 135–142, Jun. 2006, doi: 10.17660/ActaHortic.2006.710.12.

[31] S. Hemming, S. L. Speetjens, D. Wang, and J. R. Tsay, "Greenhouse design for vegetable production in subtropical climate in Taiwan," *Acta Hortic*, vol. 1037, no. 1037, pp. 65–74, May 2014, doi: 10.17660/ActaHortic.2014.1037.4.

[32] J. B. Campen and G. P. A. Bot, "Determination of Greenhouse-specific Aspects of Ventilation using Three-dimensional Computational Fluid Dynamics," *Biosyst Eng*, vol. 84, no. 1, pp. 69–77, Jan. 2003, doi: 10.1016/S1537-5110(02)00221-0.

[33] M. L. García-Balaguer *et al.*, "Mobile shading versus whitewashing: Evaluation of the agronomic response of a tomato crop," *Acta Hortic*, vol. 1170, pp. 959–965, Jul. 2017, doi: 10.17660/ACTAHORTIC.2017.1170.123.

[34] B. Rabbi, Z. H. Chen, and S. Sethuvenkatraman, "Protected Cropping in Warm Climates: A Review of Humidity Control and Cooling Methods," *Energies 2019, Vol. 12, Page 2737*, vol. 12, no. 14, p. 2737, Jul. 2019, doi: 10.3390/EN12142737.

[35] M. Amani, S. Foroushani, M. Sultan, and M. Bahrami, "Comprehensive review on dehumidification strategies for agricultural greenhouse applications," 2020, doi: 10.1016/j.applthermaleng.2020.115979.

[36] J. I. Montero, P. Muñoz, M. C. Sánchez-Guerrero, E. Medrano, D. Piscia, and P. Lorenzo, "Shading screens for the improvement of the night time climate of unheated greenhouses," *Spanish Journal of Agricultural Research*, vol. 11, no. 1, pp. 32–46, Jan. 2013, doi: 10.5424/SJAR/2013111-411-11.

[37] O. Van Der Valk, “Mexican protected horticulture: Production and market of Mexican protected horticulture described and analysed,” 2011. [Online]. Available: www.lei.wur.nl.

[38] L. J. Pilkington, G. Messelink, J. C. van Lenteren, and K. Le Mottee, “‘Protected Biological Control’ – Biological pest management in the greenhouse industry,” *Biological Control*, vol. 52, no. 3, pp. 216–220, Mar. 2010, doi: 10.1016/j.biocontrol.2009.05.022.

[39] G. J. Messelink and M. H. Kruidhof, “Advances in pest and disease management in greenhouse cultivation,” in *Achieving sustainable greenhouse cultivation*, 1st ed., L. Marcelis and E. Heuvelink, Eds., Burleigh Dodds Science Publishing, 2019, pp. 311–356. Accessed: Nov. 27, 2023. [Online]. Available: https://www.taylorfrancis.com/chapters/edit/10.1201/9780429266744-11/advances-pest-disease-management-greenhouse-cultivation-gerben-messelink-marjolein-kruidhof.

[40] J. C. van Lenteren, K. Bolckmans, J. Köhl, W. J. Ravensberg, and A. Urbaneja, “Biological control using invertebrates and microorganisms: plenty of new opportunities,” *BioControl*, vol. 63, no. 1, pp. 39–59, Feb. 2018, doi: 10.1007/S10526-017-9801-4.

[41] G. J. Messelink, M. W. Sabelis, and A. Janssen, “9 Generalist Predators, Food Web Complexities and Biological Pest Control in Greenhouse Crops”.

[42] G. J. Messelink *et al.*, “Approaches to conserving natural enemy populations in greenhouse crops: current methods and future prospects,” *BioControl*, vol. 59, no. 4, pp. 377–393, Aug. 2014, doi: 10.1007/s10526-014-9579-6.

[43] J. Pijnakker, D. Vangansbeke, M. Duarte, R. Moerkens, and F. L. Wäckers, “Predators and Parasitoids-in-First: From Inundative Releases to Preventative Biological Control in Greenhouse Crops,” *Front Sustain Food Syst*, vol. 4, p. 595630, Dec. 2020, doi: 10.3389/FSUFS.2020.595630/BIBTEX.

[44] A. N. Shylesha, B. S. Bhumannavar, and N. K. K. Kumar, “Classical Biological Control Initiatives for the Impending Invasive Pests of India,” *Journal of Biological Control*, pp. 7–30, Jul. 2012, doi: 10.18311/JBC/2012/3506.

[45] S. Joshi and C. R. Ballal, “Syrphid predators for biological control of aphids.,” *Journal of Biological Control*, vol. 27, no. 3, pp. 151–170, 2013.

[46] A. N. SHYLESHA and A. SRAVIKA, “Natural occurrence of predatory bugs, Eocanthecona furcellata (Wolff) and Andrallus spinidens (Fabr.) on Spodoptera frugiperd (Smith) (Hemiptera:Pentatomidae) in maize and their potential in management of fall army worm,” *Journal of Biological Control*, vol. 32, no. 3, pp. 209–211, Sep. 2018, doi: 10.18311/jbc/2018/22477.

[47] S. Sharanabasappa, C. M. Kalleshwaraswamy, J. Poorani, M. S. Maruthi, H. B. Pavithra, and J. Diraviam, “Natural enemies of Spodoptera frugiperda (J. E. Smith) (Lepidoptera: Noctuidae), a recent invasive pest on maize in South India,” *Source: The Florida Entomologist*, vol. 102, no. 3, pp. 619–623, 2019, doi: 10.2307/48563335.

[48] K. Choudhary, S. Kumar, D. Sharma, K. Ruchika, K. Thakur, and J. Yangchan, “A review on destructive tomato pest, <i>Phthorimaea absoluta</i> (Lepidoptera: Gelechiidae) and its management,” *Journal of Biological Control*, vol. 36, no. 3, pp. 84–93, Jun. 2023, doi: 10.18311/jbc/2022/28704.

[49] M. C. Keerthi, A. Sravika, H. S. Mahesha, A. Gupta, H. A. Bhargavi, and S. Ahmed, “Performance of the native predatory bug, Eocanthecona furcellata (Wolff) (Hemiptera: Pentatomidae), on the fall armyworm, Spodoptera frugiperda (J. E. Smith) (Lepidoptera: Noctuidae), and its limitation under field condition,” *Egypt J Biol Pest Control*, vol. 30, no. 1, p. 69, Dec. 2020, doi: 10.1186/s41938-020-00272-7.

[50] T. M. Manjunath, “Integration of augmentative biocontrol with synthetic pesticides and other control methods for IPM – Challenges and prospects*,” *Journal of Biological Control*, vol. 36, no. 4, pp. 179–186, Aug. 2023, doi: 10.18311/jbc/2022/34091.

[51] “ITMU | Patents.” Accessed: Nov. 23, 2023. [Online]. Available: https://databases.nbair.res.in/ITMU/tech_view.php.

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