

CONTROLLED ENVIRONMENT HORTICULTURE

WHERE PLANT BIOTECHNOLOGY
MEETS SUSTAINABLE FUTURE



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Controlled Environment Horticulture: Where Plant Biotechnology Meets Sustainable Future

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FOREWORD I

The Controlled Environment Horticulture (CEH), which encompasses greenhouse gardening and vertical farming, is a promising approach to food production that combines the benefits of plant biotechnology with sustainable practices. It offers greater control over environmental factors like light, temperature and nutrients, leading to higher yields, improved quality, reduced environmental impact and year-round production.

This book offers a comprehensive examination of the present state of Controlled Environment Horticulture (CEH), highlighting its historical origins and delving into different methods of protected cultivation. It highlights the numerous challenges faced by plants, such as nutrient shortages, salt stress and pollution, while providing practical solutions for addressing these problems in controlled settings. A key merit of this book is its exploration of the crucial impact of biotechnology on the progress of CEH. It covers significant breakthroughs in photobiology and the detailed analysis of plant metabolites, showcasing the scientific innovations that are broadening the possibilities within horticulture. Furthermore, the book discusses the emergence of cutting-edge farming methods, including vertical farming, hydroponics, aeroponics, aquaponics, demonstrating how these approaches are transforming agriculture and contributing to a sustainable future. This book emphasizes practical applications, featuring specific chapters on the protected cultivation of various crops such as fruits, vegetables, flowers and medicinal plants.

I am sure that this book, would serve not just as a repository of information but as an essential tool for researchers, students, farmers and entrepreneurs dedicated to the advancement of sustainable agriculture. My aspiration is that it sparks fresh ideas and innovations, motivating everyone who interacts with it to play a role in building a more resilient and sustainable food system for future generations. At this pivotal moment in the intersection of agricultural advancement and environmental responsibility, we should harness the capabilities of Controlled Environment Horticulture to revolutionize our food production methods and secure a sustainable future for everyone. Finally, I would like to extend my congratulations to all the authors of the book chapters and the Bentham Science International Publishers, Singapore for bring this book in print media.

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FOREWORD II

In a world facing increasing challenges like food insecurity, climate change, and shrinking arable land, finding sustainable ways to grow food has never been more urgent. Controlled Environment Horticulture (CEH) offers a promising solution by creating ideal conditions for plants to thrive, regardless of external factors. This book, *Controlled Environment Horticulture: Where Plant Biotechnology Meets Sustainable Future*, brings together the key principles, practices, and forward-looking innovations in CEH, where science meets sustainability.

The chapters of this book cover a wide range of topics that give a clear picture of the current state of CEH and its future potential. Starting with the basics and the history of controlled environment growing, we explore different systems of protected cultivation and how environmental factors like light, temperature, and humidity play a crucial role. It also tackle the challenges plants face-such as nutrient deficiencies, salt stress, and pollution-and how we can manage these stresses within controlled environments.

One of the most exciting aspects of this book is the exploration of biotechnology's role in advancing CEH. From breakthroughs in photobiology to the study of plant metabolites, this book delves into the scientific innovations that are pushing the limits of what is possible. It also focuses on the rise of vertical farming, hydroponics, aeroponics, and aquaponics, showing how these systems are transforming agriculture and contributing to a sustainable future.

Practical applications are also highlighted, with chapters dedicated to the protected cultivation of fruits, vegetables, flowers, and medicinal plants. Weed management, pest and disease control, and the economics of CEH are discussed to provide a well-rounded view of the operational side of running these systems. The book concludes with a look at the global trends shaping the future of CEH and the exciting prospects that lie ahead.

This book is meant to be a valuable resource for researchers, students, farmers, or entrepreneurs—who are passionate about the future of sustainable agriculture. More than just a book, I hope it sparks new ideas and innovations that will help us build a more resilient and sustainable food system for future generations.

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PREFACE

The Indian population faces several issues today, including rapid urbanization, population growth, resource depletion, and decreasing nutrition security. With its potential to improve nutrition security, increase in local crop output, decrease transportation of food, and use of less resources, controlled environment horticulture, or CEH, might completely transform our food systems. CEH systems-greenhouses, vertical farms, and high tunnels-allow the management of environmental factors, including temperature, air quality, light intensity, duration, and CO₂, to provide predictable production and quality responses. The cultivation of high-value, ornamental, fruit, and fresh food crops is made possible by these systems all year round. The high energy consumption, manpower (training and automation), better temperature control, phytonutrient enhancement, sustainability, and labor costs remain significant challenges for production development. In horticulture, this term refers to production beneath structures like covers, artificial shade, plastic tunnels, or greenhouses.

Horticulturists or researchers can use various stress reactions to add beneficial elements to fruits, vegetables, or medicinal plants. For example, a plant can start defense reactions, such as the production of bioactives, after a mild stress event is introduced in a controlled manner (such as a shortage of water, high temperature, or nutrients); however, the stress intensity is controlled so that biomass formation is not affected.

This book, *Controlled Environment Horticulture: Where Plant Biotechnology Meets Sustainable Future*, goes into great detail on how horticulturists, students, researchers, and farmers can manage biotic and abiotic production variables to modify crop metabolism and produce beneficial metabolites, whether used as plant-based medications or as a component of a plant-based diet. A theoretical backdrop is offered prior to recommendations in this area. It enables the reader to use the knowledge they have learned in many contexts. The distinctive quality of this book stems from the fact that several chapters have been written by experts and scientists from India, Malaysia, Germany, South Africa, and Nigeria. This book's style makes it ideal for undergraduate students, readers, learners, and farmers since it simplifies and makes sense of complicated plant physiological principles in a controlled environment.

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DEDICATION

This book is dedicated to Swamiji, students, our loving parents, and to the one whom I love.

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CHAPTER 1

Introduction to Controlled Environment Horticulture

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Abstract: Controlled environment horticulture (also called protected structure cultivation), the concept of cultivating horticultural crops in protected structures, dates back to 14 AD. This method of cultivation offers protection to crops by regulating environmental factors (both biotic and abiotic factors) as per the crop's requirements while reducing the incidence of pests and diseases. This chapter elucidates the diverse designs of protected structures in controlled environment horticulture, tailored to meet the growth requirements of various or specific crops. The regulations of environmental conditions (such as light, temperature, humidity, ventilation, water, nutrients, and pests) and the mechanisms of achieving optimum growing conditions are also highlighted. The huge initial investment and operational costs of controlled environment horticulture are stressed, and the need for improvement in the various designs is advocated to achieve energy sustainability while reducing costs.

Keywords: Controlled environment, Disease, Humidity, Light, Management, Nutrients, Nutrient pest, Soil, Substrate, Temperature.

INTRODUCTION

The term horticulture is a derivative of the Latin words *hortus*, meaning 'garden', and *cultura*, meaning 'cultivation' [1]. Simply put, horticulture is the cultivation of crops in an enclosure, *i.e.*, in a garden. The concept of horticulture as "garden cultivation" is overly simplistic, as it does not present the categories of crops associated with this type of cultivation. In a broader view, horticulture is considered an aspect of agriculture that focuses on the cultivation of plants for flowers, fruits, vegetables, medicines, aroma, and aesthetics (or beauty). [2] A study defined horticulture as the science of cultivating vegetables, herbs, fruits, nuts, and ornamental plants (including turfs, grasses, shrubs, and trees) [3]. Another study considers horticulture to include the art, science, technology, and business of gardening vegetables, fruits, flowers, seeds, and nuts.

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According to von Baeyer (2024) [2], horticultural practice dates back to about 20 millennia, when hunters and gatherers embarked on the trial-and-error approach of domesticating wild plants collected from diverse ranges in an attempt to breed the food closer to their shelters. Although agriculture and horticulture could be said to have begun at a time and evolved together, the approaches of these two fields differ considerably in terms of production, specialisation, and commercialization. Modern agriculture is often carried out on large expanses of fields and involves mono-crops in order to adapt cropping to mechanised processes of cultivation, harvesting, and processing. Its main goal is to promote the commercial production of food and food-related items, including livestock. Contrastingly, horticulture includes production that takes place in both open spaces (such as gardens, lawns, and parks) and enclosed areas (such as screen houses and greenhouses) and supports the mixing of varieties of plants (including fruits, vegetables, medicinal, and ornamental plants) in an area or space, as opposed to their seclusion in separate rows or plots. This approach offers great physiological and environmental benefits such as efficient nutrient and moisture utilisation, optimum photon trapping, and exploitation of micro-environmental variation leading to increased photosynthetic efficiency. For example, intercropping legumes (such as purple-hulled peas, garden peas, snap beans, and yard-long beans) with vegetable crops is being promoted in sustainable horticultural practices to reduce reliance on chemical inputs such as fertilisers [4].

Horticulture is an important aspect of the farming system that is aimed at advancing the quality of life of man as well as the beauty, sustainability, and restoration of the ecosystem. These goals are achieved through the production of healthy and nutritious food, promotion of biodiversity, improvement of ecosystem aesthetics, mitigation of climate change through the reduction of carbon footprint, and improvement of air quality and living conditions of organisms. Horticulture deals with a great variety and diversity of plants, thus acting as a major driver for agricultural and economic diversification.

Horticulture is classified on the basis of the major categories of crops it deals with. The major branches of horticulture include pomology, the production of fruit crops, olericulture, the production of vegetable crops, and floriculture, the production of ornamental plants. In recent times, landscaping- the art of enhancing the beauty of the visible features of an area of land through the modification of its terrain, plant arrangements, and the installation of patios, walkways, and other spaces- has become an integral part of horticulture. Landscape gardening is an evolving and aesthetic branch of horticulture that deals with the design of landscapes using ornamental plants in a fashionable way that presents a picturesque.

Controlled Environment Horticulture (CEH) refers to the gardening of specialty crops, including fruits, vegetables, spices, ornamental and aromatic plants, and mushrooms, within protected structures or indoor systems, such as screen houses, greenhouses, vertical farms/plant factories, and other facilities, where advanced technology is employed to control the environmental conditions such as temperature, humidity, lighting, gaseous exchange, pests, and pathogens.

The horticultural practice of cultivating crops in controlled environments, also known as protected cultivation, dates back to ages, with the earliest record around 14 AD in Rome, where cucumber plants (*Cucumis sativus* L.) were grown in prototype greenhouses (called *specularia*) constructed for Emperor Tiberius (42 BC–37 AD) presumably beside his palace on the Island of Capri [5, 6]. This was done to evade the cold winter season and get cucumbers year-round for the Emperor. It was on record that there was never a time the gardeners failed to meet the Emperor's demand for the fruit [6]. Protected structures offer protection to crops by regulating environmental factors (both biotic and abiotic factors) as per the crop's requirements. These structures can be used to prevent, delay, or even mitigate pest and disease incidences in crops by modifying the environmental conditions (such as temperature, humidity, and other factors) against pests and pathogens. Controlled environment horticulture thus offers the immense advantage of producing healthier crops with improved yields and quality in stark contrast to traditional gardening or farming, which relies on environmental impulses and can be significantly impacted by extreme conditions like excessive heat, frosts, droughts, and floods. Protected structures are used to regulate conditions of growth by creating perfectly balanced environments that meet the requirements of crops, allowing for all year-round production. Not only does this environmental control ensure consistent production and yield, but it also allows for the cultivation of crops in places that are traditionally unsuitable for them [7].

There are various types of protected structures employed in modern horticulture. These structures can be categorised on the basis of materials used and structure designs. Materials commonly used in the design of protected structures for controlled environment horticulture (CEH) include glass sheets, polycarbonate sheets, plastic films, and polyethylene films and nets (also called HDPE nets—high-density polyethylene nets). Different structures used in controlling environmental factors in horticulture include greenhouses, polyhouses, net houses, raised beds, trellis, and drip irrigation systems. These structures are being used independently or in combination to offer optimum growing conditions and protection against severe weather conditions, pests, and pathogens while allowing for out-of-season or year-round planting [7].

CHAPTER 2

History of Controlled Environment Horticulture**Parth M. Mangroliya^{1,*} and Yash G. Desai²**¹ *ASPEE College of Horticulture, Navsari Agricultural University, Navsari, Gujarat, India*² *Parul University, Vadodara, Gujarat, India*

Abstract: Intensive agricultural techniques designed for optimal output and efficiency are evident in modern greenhouses. In greenhouses, plants are cultivated year-round by maintaining environmental conditions close to ideal levels, even in the face of inclement weather. The past two centuries have seen a great deal of scientific and technical progress, which has led to the development of modern greenhouses. These include innovations in temperature control, artificial lighting, hydroponic farming systems, and glass and structural designs tailored to certain climates. According to Pliny, Emperor Tiberius was “always provided with this delicacy; in fact, he had a special partiality for it.” The *Cucumis* fruits that Pliny and Columella mentioned were really long-fruited (*Cucumis melo* subsp. *melo*), which were mistranslated as cucumbers. In ancient Israel and Rome, these were highly prized vegetables that are today known as faqqous, veggie melons, and snake melons. With 90% of farmers stating that their consumers would pay more for crops with enhanced taste, producers overall found that improving agricultural flavor through growing environment management and expanding production practices were the most pertinent study areas. Finally, based on historical facts and existing practices, prospects for future hydroponic CE production were explored. These include the need to investigate several environmental factors rather than just one and the focus on improving crop quality, including flavor, sensory attributes, and postharvest longevity, in addition to production.

Keywords: Artificial, Controlled condition, Glazing, Heating, High yield, Infrastructure, Modern greenhouse, Production.

INTRODUCTION

The art of greenhouse technology involves cultivating crops within structures with a transparent covering to shield them from harsh weather and bad climate conditions. In addition to greenhouses, additional forms of protected agriculture include row covers, net houses, and low and high tunnels. The main features that differentiate a single greenhouse apart from another are the type of structural

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elements used in its construction and the degree of technology used. In the 19th century, greenhouses were operated as hobbies, but by the 21st century, they were completely commercialized. Countries like Israel and the Netherlands have sizable greenhouse zones and are also important providers of greenhouse technology to other emerging nations. The greenhouse sector has been growing as a result of design technology advancements, affordable and long-lasting glazing materials, environmental control, and soilless farming. The most recent commercial platform for producing specialized crops under cover does not require sunshine. In reality, all of the cardinal variables of plant growth (light, temperature, water, nutrients, and environment) must be provided and managed in order to grow crops for indoor harvesting. The umbrella term “controlled-environment agriculture” (CEA) encompasses various appellations such as “indoor agriculture” (IA), “indoor farming” (IF), “vertical farming” (VF), “plant factories” (PF), “container farms” (CF), and more. By managing these cardinal parameters, fresh food may be grown quickly and productively indoors year-round, independent of outside climatic or meteorological circumstances. Complete environmental control provides clear benefits for growing perishable products with a short shelf life, particularly in terms of avoiding quality loss and the costs associated with long-distance transportation.

History of Greenhouse

Between 14 and 37 CE, the earliest documentation of crop cultivation in protected environments appeared in Rome [1]. Emperor Tiberius is noted for growing cucumber plants throughout the year using artificial techniques. During chilly nights, these plants were moved on carts to sheltered homes known as *Specularia*. The importance of protected agriculture is also discussed in “*Sanga Yorok*,” a crop husbandry treatise from the 1450s by the royal physicist of the Joseon dynasty in Korea. This text explains how to cultivate mandarin trees and produce mature fruit using *Ondol*, a traditional underfloor heating system. In winter, fruit trees, such as potted oranges, were relocated within these structures to protect them from the elements. Furthermore, recent research has shown that staff at Wye House engaged in agricultural trials focused on medicinal and nutraceutical plants [2]. In the 19th century, large glasshouse conservatories were created in Europe to cultivate exotic tropical plants brought in from other regions. Noteworthy examples include the iron-framed glasshouses constructed at the Royal Botanic Society in Regent's Park (1842-46) and the Royal Horticultural Society in Chiswick (1840).

Hydroponic production enables plant growth without mineral soil by using inert mediums such as gravel, sand, peat, vermiculite, perlite, coco coir, sawdust, and rice hulls, which supply essential nutrients [3]. While traditional hydroponic

methods have often excluded soilless substrate techniques, these are commonly used in potted floriculture. In this study and in the USDA Census of Horticultural Specialties, crops grown in nutrient solutions without soil are classified as hydroponic [4].

Greenhouse Designs

Modern commercial greenhouses have evolved significantly from the Orangeries of the 18th century and the glasshouses of the 19th century. Many designs were tailored to suit local climates. In the 20th century, the Westland region of the Netherlands became a center for greenhouse development. These Westland-style structures featured removable glass panels that allowed winter rains to wash away soil salt buildup [5].

While these greenhouses improved upon older grape cultivation designs, they were not well insulated due to gaps between the panels. The devastation of World War II led to extensive damage, with approximately 1.8 million square meters of glass destroyed [5].

In the aftermath, engineers in Venlo created a tall, multispan-insulated greenhouse design. This new approach aimed to fulfill post-war demands for vegetables and other crops. Over the years, the Venlo design has been refined to lower costs and enhance ventilation, making it suitable for regions with less wind. Today, Venlo is recognized as a global leader in greenhouse innovation [6]. In China, the production of protected crops began to rise in the 1980s, aided by the country's "open-door" policy established in 1978. This policy allowed for the import of modern greenhouse designs, including the Venlo style. However, due to their high costs, these greenhouses did not see widespread adoption. Instead, Chinese manufacturers created designs that better fit local conditions [7]. One significant advancement is the solar greenhouse, a cost-effective structure made from plastic or glass. Developed initially in Liaoning Province, these greenhouses utilize passive solar energy for heating during the day and retain warmth at night with thermal blankets and north-facing brick walls [8]. This design has proven effective in boosting production in China's colder northern regions. By the end of the 20th century, the area dedicated to protected agriculture, mainly solar greenhouses, was estimated at around 1.4 million hectares, with more recent estimates suggesting closer to 2 million hectares [9].

In Spain, a sizable greenhouse business has been rapidly growing during the last thirty years, particularly in an area near the Mediterranean called Almeria in southeast Spain. Principal commercial greenhouse designs found around the globe include (A) Venlo fashion, (B) Vegetable Crops, (C) Parral fashion, and (D) Polyhouse with gutter connections. Around 26,000 hectares of greenhouses,

CHAPTER 3

Types of Protected Structures in Controlled Environment Horticulture

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Abstract: Protected cultivation encompasses techniques such as greenhouses, net houses, and advanced systems like hydroponics and aeroponics, which represents a transformative approach in modern agriculture. By offering a controlled environment, it ensures optimal growth conditions, leading to enhanced productivity, consistent quality, and year-round cultivation. This method reduces the reliance on chemical inputs and mitigates the impact of adverse weather, contributing significantly to sustainable farming. Though it requires substantial initial investment and technical knowledge, the long-term benefits, including higher yields and improved crop resilience, make protected cultivation a vital tool for addressing global food security and environmental challenges. The present chapter explores the types of protected cultivation and illustrates how farmers may use it to extend growing seasons, protect crops from adverse conditions, and maximize resource use, highlighting its potential to create sustainable livelihoods and increase agricultural productivity.

Keywords: Environment, Greenhouse, Net house, Production, Protected cultivation, Quality, Shade house.

INTRODUCTION

Definition of Protected Cultivation

Protected cultivation refers to the practice of growing plants in a controlled environment, such as a greenhouse or polyhouse, where temperature, humidity, light, and other factors can be managed to optimize growth and protect crops from adverse weather, pests, and diseases.

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This method is vital in modern agriculture as it allows for year-round production, improves crop quality and yields, and reduces the impact of adverse weather conditions, pests, and diseases, contributing to food security and sustainability [1].

Importance of Protected Cultivation

Enhanced Productivity

- **Optimal Growing Conditions:** These are the conditions that plants receive, such as ideal temperatures and humidity and light levels, which can lead to higher growth rates and increased yields.
- **Extended Growing Seasons:** By protecting crops from adverse weather conditions, such as frost or excessive rain, you can grow plants throughout the year, allowing for multiple harvests annually.
- **Reduced Pest and Disease Pressure:** It ultimately reduces crop losses and potentially increases productivity [2].

Quality Control

- **Consistent Quality:** Controlled conditions contribute to uniform growth and development, which can lead to more consistent fruit size, color, and taste.
- **Reduced Chemical Use:** With fewer pests and diseases, there is often less need for pesticides and fungicides, resulting in cleaner and higher-quality produce.
- **Better Post-Harvest Quality:** Reduced stress on plants leads to better-quality produce that can often be stored and transported more effectively [3].

Year-Round Cultivation

- **Continuous Production:** By controlling environmental factors, you can grow crops year-round regardless of outside weather conditions, ensuring a steady supply of produce.
- **Diversified Crop Options:** Different crops can be grown in different seasons or climate-controlled conditions, allowing for a diverse range of products throughout the year.
- **Market Stability:** Year-round cultivation helps stabilize market supply, which can be beneficial for both producers and consumers [4].

Types of Greenhouses

Types of Greenhouses (Fig. 1) are discussed below:



Fig. (1). Different types of greenhouse.

- **Based on Structural Design:** A-frame, Quonset, Lean-to type greenhouse, etc.
 - i. A **lean-to greenhouse** is built against an existing structure, using one wall for support, which saves space and reduces construction costs. This design benefits from the shared wall's insulation, making it more energy-efficient. It is ideal for small gardens or urban settings and provides easy access to utilities like water and electricity from the adjoining building [5].
 - ii. A **ridge and furrow greenhouse** consists of a series of connected greenhouses with a central gutter, creating a sawtooth pattern. This design maximizes natural light and provides efficient drainage, making it suitable for large-scale farming. The structure's continuous interior space enhances airflow and temperature regulation, promoting consistent growing conditions for crops [5].
 - iii. An **Even span greenhouse** is designed with a steeply pitched roof, allowing for efficient snow and rain runoff. It maximizes sunlight exposure, particularly in winter, and is easy to construct and maintain. This design also provides excellent stability in windy conditions and is space-efficient for small gardens [5].
 - iv. A **Gothic arch greenhouse** features a high, pointed roof that enhances snow and rain runoff while providing superior structural strength. Its design allows for more vertical growing space and improved light diffusion, which supports healthier plant growth. The Gothic arch shape also withstands harsh weather conditions, making it ideal for areas with heavy snow or strong winds [6].
 - v. An **uneven span greenhouse** has one roof slope longer than the other, making it ideal for construction on hilly or uneven terrain. This design maximizes sunlight exposure on the longer slope, enhancing plant growth. It is especially useful in areas with limited flat land and offers better insulation and temperature control in colder climates [6].
 - vi. A **Quonset greenhouse** offers durability and ease of construction. Its curved design promotes even heat distribution and efficient airflow,

CHAPTER 4

Environmental Factors and Controlled Environment Horticulture: Light, Temperature, and Humidity

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Abstract: Controlled environment horticulture has emerged as a modern method of protected horticulture, taking place entirely indoors without the benefit of natural sunlight. While it may seem impractical for commercial production, this approach originated from researchers aiming to systematically investigate how specific environmental factors affect plant growth and development, isolating them from uncontrolled variables that could skew results. As technology for indoor plant production has advanced, energy requirements for growing plants in fully controlled environments have significantly decreased. This evolution has led to the development of a new sector within controlled environment horticulture. This chapter explores key environmental factors—light, temperature, and humidity—highlighting their importance and how they are integrated into controlled environment practices. By understanding these factors, growers can optimize conditions to enhance plant growth and productivity in indoor settings.

Keywords: Agriculture, Cost-benefit, Controlled condition, Factors, Horticulture, Light, Operation, Protected cultivation, Radiation, Semperature.

INTRODUCTION

Controlled environment horticulture (CEH) has emerged as a modern approach to protected horticultural practices, carried out entirely indoors without access to natural sunlight. Although it may seem less than ideal for commercial horticultural production, the concept of indoor plant cultivation originally stemmed from researchers' efforts to systematically study the effects of specific environmental factors on plant growth and development without interference from uncontrolled variables. As technology supporting indoor plant production has advanced in both capability and efficiency, energy demands have significantly

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decreased for growing plants throughout full production cycles in fully controlled environments. This progress has given rise to a new sector within controlled environment horticulture [1].

Controlled environment plant production utilizes structures and technologies to reduce or eliminate the potential negative effects of weather on plant growth and development. Common structures include greenhouses, indoor growing facilities like plant factories, and growth chambers. Although each type of facility presents its own challenges, many of the processes, principles, and technological solutions are similar across different environments [2].

Controlled environment horticulture (CEH) has the potential to revolutionize food systems by enhancing nutritional security, increasing local crop yields, lowering food transportation distances, and minimizing resource consumption. CEH systems—such as greenhouses, vertical farms, and high tunnels—enable precise management of environmental factors, including light, temperature, humidity, and air composition (CO₂ and oxygen), leading to consistent yield and quality results. These systems support year-round production of fresh produce, ornamental plants, and high-value crops. However, escalating production costs reveal critical areas for improvement, such as reducing energy consumption, increasing labor efficiency through training and automation, optimizing climate control using both traditional and AI approaches, enhancing phytonutrient levels, and advancing sustainability efforts [2].

LIGHT IN CEH

According to researchers, light is a crucial component of photosynthesis and plays a key role in temperature regulation. The use of light in controlled environment horticulture (CEH) has garnered significant attention from both the research and commercial sectors. Since indoor horticulture lacks natural sunlight, artificial lighting becomes the primary factor influencing plant growth and productivity. Supplementing light in greenhouses enhances both productivity and quality, particularly in northern hemisphere countries where light is limited during autumn and winter. Assimilation lighting is commonly used to control both photoperiod and light intensity, with increasing interest now focused on the quality of light as well [2].

Inside a polyhouse, light can be categorized into three types based on wavelength. The most crucial type is visible light in the range of 400-700 nm, which drives photosynthesis in plants. It is referred to as Photosynthetically Active Radiation (PAR). Different wavelengths are used during various stages of plant growth. Blue light, ranging from 400-490 nm, is essential for the vegetative and foliage growth phase, while orange-red light, between 590-700 nm, is important for the

flowering and fruiting stage. Green light, in the 490-580 nm range, has minimal impact on plant growth because plants naturally reflect green light, as their chloroplasts absorb blue and red light more effectively [3].

Types of Lights Used in Controlled Environment Horticulture (CEH)

- **HID (High-Intensity Discharge):** HID bulbs produce light by passing electricity through a gas-filled tube. They have low installation costs and emit light in the red and orange spectrum, making them ideal for plants during the flowering stage.
- **Fluorescent:** Fluorescent bulbs or tubes use fluorescence to produce visible light but emit less light compared to HIDs. They are often used for seed germination, rooting of cuttings, and early to mid-stage vegetative growth. Two common types of fluorescent lights include tube-style and compact fluorescent lights (CFLs).
 - **Tube-Style Lights:** There are various forms of tube-style fluorescent lights, such as T5, T8, and T12, with T5 being the most efficient and popular. T5 bulbs are cooler than HIDs and can be placed closer to plants due to their lower power output.
 - **Compact Fluorescent Lights (CFLs):** These are short, spiral-shaped bulbs that are a smaller version of traditional fluorescent lights. CFLs are ideal for smaller growing spaces.
- **LED (Light Emitting Diode):** LED grow lights have gained popularity in commercial greenhouses due to their energy efficiency, low heat emission, and low maintenance needs. They can be customized to emit specific wavelengths of light, offering many advantages for indoor plant growth. With precise control over the light spectrum, LED lighting can influence plant morphology, nutrient content, metabolite production, flavor, growth rate, fruiting, flowering, color, and overall plant health. This high degree of control even allows for phenotype tuning within the same plant species.

LEDs function as semiconductor devices that convert electrical energy directly into light energy by facilitating the radiative recombination of electrons and holes within a semiconductor's bandgap. The emitted light's wavelength is determined by the bandgap energy of the semiconductor material. In compound semiconductors like indium gallium nitride (InGaN), the bandgap can be adjusted to produce LEDs that emit different wavelengths of light [4].

While sunlight provides a full spectrum of light, including harmful UV rays and heat-inducing infrared radiation, greenhouses allow farmers to modify sunlight using infrared-blocking panels or cooling systems to manage crop temperatures. In contrast, indoor LED lighting offers superior control over light quality,

CHAPTER 5

Plant Stresses and Controlled Environment Horticulture: Salt Stress, Metal Pollution, Nutrient Deficiency, and Wounding

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Abstract: Plants experience stress when environmental conditions are suboptimal for growth, influenced by both biotic factors (such as pests) and abiotic factors (such as salinity, drought, and nutrient deficiencies). These stresses can significantly impact plant yield and quality. In response to the challenges posed by climate change and increasing global food demands, controlled environment horticulture (CEH) has emerged as a transformative approach to mitigating plant stress. This chapter explores how CEH provides a superior alternative for managing environmental factors that limit horticultural plant growth. It will discuss the resistance traits that plants develop to cope with abiotic stress and examine the advantages and challenges associated with CEH. Additionally, the chapter will address types of growing methods in a controlled environment.

Keywords: Abiotic factors, Climate, Controlled condition, Crops, Drought, Metal pollution, Nutrient deficiency, Salinity, Stress, Wounding.

INTRODUCTION

Horticultural crops, including fruits, vegetables, medicinal, aromatic, and ornamental plants, are frequently exposed to stress, especially in field conditions. Stressors, both biotic and abiotic, are key factors limiting the productive capacity and nutritive quality of crops [1]. Horticultural crops contribute significantly as dietary nutritional components, serve as sources of medicines and aromatic products, and offer great aesthetic value to man [2].

Stress is a concept in the fields of plant physiology, plant biochemistry, and ecophysiology that relates to environmental constraints that affect plant growth,

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development, and yield. It creates internal or external restrictions that lower a plant's capacity to convert energy from light into biomass as a result of a limit in photosynthetic rate [3]. Crops are said to be undergoing stress or stressed when growth-promoting environmental conditions are not met. Crops react to stress in a variety of ways, varying in growth rates, crop yields, cellular metabolism, gene expression, and so on. However, stress-tolerant crop species that are exposed to a certain stress eventually acquire resistance to that specific stress [4].

TYPES OF CROP STRESS

Crops are exposed to a variety of stresses that can be categorized into two broad categories: biotic and abiotic stresses. Biotic stress refers to stress conditions induced by biotic agents (living organisms), viruses, bacteria, fungi, nematodes, insects, arachnids, and weeds, which can lead to mortality or injury as a result of nutrient depletion in crops [4, 5].

Abiotic stress, on the other hand, refers to any environmental factor such as drought, nutrient insufficiency, salt stress, metal pollution, and wounding that restricts plant growth, development, and output [6]. Abiotic stress has historically drawn the attention of plant scientists and agronomists in the last fifty years because of the significant increase in the human population, which has jeopardized world food security. Boyer (1982) predicted in the early 1980s that environmental conditions might cut crop productivity by up to 70% [7]. Ever since, a number of studies mentioning crop loss as a result of different abiotic stresses have been published [8, 9].

A few of these stressors damage farmed soils permanently, which eventually affects crop quality and productivity. A rough calculation based on FAO figures indicates that approximately 96.5% of worldwide rural land is influenced by abiotic pressures, despite the fact that it is difficult to evaluate the impacts of abiotic stresses on agricultural fields. Abiotic stress, such as heat stress, cold stress, drought, salinity, metal pollution, and waterlogging, can reduce plant tolerance and increase susceptibility to biotic stress, such as disease infestation [10].

According to a study [11], abiotic stress presents a variety of responses in plants ranging from molecular to cellular and from genomic to metabolic interactions. Some of the major abiotic stress that affect crops in protected structure cultivation include:

- Salt stress
- Nutrient deficiency

- Metal pollution
- Wounding

Salt Stress

Salt stress occurs due to a rise in the salt content of the soil. This is also called salinity stress, soil salinity, or salinization. Salt stress is defined as an increase in the amount of salt in the soil [12]. It is a common occurrence in semi-arid and arid areas where plants experience greater rates of transpiration and evaporation than precipitation volume all year long. Primary soil salinity is the result of naturally occurring salt accumulation in the subsurface; secondary soil salinity is the result of human-caused situations such as environmental contamination. Changes in soil composition, increased fertilizer use, or irrigation with saline water can all lead to secondary soil salinity [13]. Soil salinity is a global issue that poses a serious risk to the entire agricultural sector, as it lowers plant productivity. Over 800 million hectares of land globally are affected by high salinity, according to a 2011 estimate [14]. Similarly, the same study predicts that by 2050, salt will harm over 17 million hectares of agricultural land. Crop growth and development are restricted by high salt concentration in a number of ways. Increased salt concentration has two important effects on crops: osmotic stress and ionic toxicity. Under normal conditions, plant cells experience a higher level of osmotic stress compared to soil. Plant cells employ this elevated osmotic pressure to take in water and essential nutrients from the soil and store them in the root cells. However, in situations where there is salt stress, the soil's osmotic pressure solution exceeds the osmotic pressure of the plant cells because of an increase in the amount of salt in the soil. This limits the ability of plants to absorb water and minerals like K^+ and Ca^{2+} , while Na^+ and Cl^- ions move within the cells and harm the cell membrane and cytosolic metabolism. Salinity-induced stress has a number of negative impacts, including decreased ROS generation, cytosolic metabolism, membrane function, and cell development. High soil salinity negatively affects both the quality and quantity of plant production by impeding seed germination and causing damage to growth and development phases because of the combined effects of greater osmotic potential and specific ion toxicity [15].

Metal Pollution

Heavy metal (HM) is classified as a non-biodegradable inorganic chemical with an atomic mass greater than 20 and a density greater than 5 g cm^{-3} . It has a toxic effect on cells and genes and mutates crops through contamination of irrigation systems, soil, drinking water, food chains, and the surrounding environment [16, 17]. Two types of metals have been found in soils: non-essential elements with unknown physiological and biological functions (Ag, Cr, Cd, Co, As, Sb, Pb, Se,

CHAPTER 6

Snapshot of Plant Biotechnology in Controlled Environment Horticulture

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Abstract: Horticulture continues to contribute towards sustaining a healthy environment, enriching our lives with a wide array of visually appealing products and adding diversity, color, and flavor to the meals we eat. The numerous advantages of horticulture are being advanced by new instruments brought about by biotechnology. Globalization and liberalization of the Indian economy have created opportunities for exporting high-value horticulture crops while also serving domestic demand. Increasing production as well as quality is vital in order to satisfy the demands of quality-conscious consumers. Beyond guaranteeing a vertical rise in productivity, an improvement in production technology is needed to integrate market-driven quality standards with the production system. “Protected cultivation,” sometimes known as greenhouse technology, is one such technique. The three primary elements that impact production and quality are cultural practices, growth conditions, and quality material. Micropropagation is a successful technique in many horticultural crops to produce disease-free planting material rapidly. Other biotechnological tools like rDNA/genetic engineering offer the scope for genetic modification of plants with desirable characteristics like resistance to biotic and abiotic factors, improvement in quality parameters, increase in crop yield, herbicide resistance, *etc.* Similarly, the use of molecular markers in genetic diversity studies and crop improvement helps in the identification of desirable genes and understanding at the molecular level. This industrial technology and the business procedures, however, come with a number of issues. Hence, the present book chapter illustrates the role of biotechnology in enhancing crop productivity in a controlled environment.

Keywords: Biotechnology, Genetic engineering, Micropropagation, Protected cultivation rDNA technology.

INTRODUCTION

Biotechnology is a multidisciplinary field that utilizes living organisms or their components to develop products and processes that benefit human society. It is

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indeed a powerful and transformative field that intersects various scientific disciplines to create innovation with profound impacts on society [1]. The techniques and applications of biotechnology are diverse and have a broad range of applications in various fields. The word biotechnology was coined by Karl Ereky (1878-1952) in Hungary in 1919 to describe the general process of converting raw materials into useful products, including a group of techniques. Furthermore, the discovery of genetic transformation in bacteria by Frederick Griffith in 1928 provided the first evidence that genetic material could be transferred between organisms, paving the way for modern genetic engineering techniques [2]. These milestones are critical in the development of plant biotechnology, which has since evolved into a sophisticated field that enables the modification and improvement of plants for agricultural and industrial purposes [3].

The Era of Plant Biotechnology is known to have begun in the early 1980s with the reports of developing transgenic plants *Agrobacterium tumefaciens* [4 - 7]. Transgenic crop commercialization demonstrated how biotechnology was effectively incorporated into plant breeding and crop development initiatives by 1996. For effective agricultural production, various biotechnological techniques can be combined, including tissue culture, genetic engineering, use of molecular markers, *in vitro* mutagenesis, cryopreservation, somatic hybridization, somaclonal variation, genetic diversity assessment, shelf-life improvement, and disease resistance for crop production [8, 9].

Horticulture is the branch of agriculture that focuses on the cultivation of plants for food, medicinal purposes, and artistic enjoyment [10]. It encompasses a wide range of activities, including the cultivation of fruits, vegetables, flowers, ornamental plants, and herbs, as well as the management of gardens, landscapes, nurseries, and greenhouses. Horticulture plays a crucial role in improving food security, enhancing the beauty of living spaces, and contributing to human health and well-being [10, 11]. As awareness of the health-protecting importance of antioxidants continues to grow, the demand for fresher, better-tasting, diverse, and nutritious fruits and vegetables will continue to expand. Most agricultural and horticultural crops have been developed by using biotechnological tools such as plant breeding [12].

Advances in biotechnology have allowed the development of disease-resistant, high-yielding, and nutritionally enhanced horticultural crops. Genetic modification, tissue culture, and molecular breeding techniques are increasingly being applied to improve horticultural plant varieties.

ROLE OF BIOTECHNOLOGY IN CROP PRODUCTION

Biotechnology has become an essential tool in horticulture, offering advanced techniques to improve the cultivation, productivity, and quality of horticultural plants. Biotechnology offers advanced solutions to some of the most pressing challenges in food production and agricultural efficiency.

Genetic Engineering of Horticultural Plants

Genetic modification is the process of changing the genetic makeup of an organism to express new traits. Genetic engineering of horticultural plants involves the direct manipulation of an organism's DNA to alter its characteristics, enhancing traits such as disease resistance, yield, nutritional content, and environmental adaptability. This advanced biotechnological approach has become a cornerstone in modern horticulture, allowing for the precise modification of plants to meet specific consumer needs.

In this technique, the gene of interest is first isolated and cloned in a vector and inserted into a host plant for transformation. Transgenic technology is the most powerful method for crop improvement and produces various crops that are resistant to pests and disease-free [13]. This technique also helps in the improvement of biofortification, extended shelf life, tolerance to environmental stress, reduced chemical use, and aesthetic and functional traits [14]. This technique is greatly used in the production of genetically modified (GM) food for large-scale cultivation. Various GM crops were first cultivated in the US on a large scale during 1995-1996, and then several GM cultivars of alfalfa and corn and various types of squashes (*Cucurbita* sp.) were released for commercial cultivation [15, 16]. In India, GM cotton varieties carrying the insecticidal protein gene from the soil bacterium *Bacillus thuringiensis* were first adopted for commercial cultivation. Two approaches of gene transfer, namely Vector-mediated gene insertion (Agrobacterium mediated, agro-infection, and viral vectors) and Direct Gene Transfer (Pollen mediated, microinjection, imbibition, etc.), are employed, of which agrobacterium mediated and particle gene transfer are most popular [17].

Some of the practical applications of rDNA technology include:

Disease Resistance

Through genetic modification, horticultural plants can be engineered to resist common diseases caused by fungi, bacteria, and viruses. In cross-protection, the presence of a mild strain of the virus in the plant protects it from subsequent infection by severe strain-related viruses. This become a common practice to

CHAPTER 7

Harnessing Light: The Role of Photobiology in Optimizing Protected Horticulture

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Abstract: The concept of photobiology in protected horticulture is applied to understand how light quality, quantity, and duration impact growth and development within a controlled environment, for example, in greenhouses or vertical farms. Light in the PAR range (400-700 nm), photosynthetically active, is an important part of photosynthesis, photomorphogenesis, and secondary metabolite formation. Artificial sources, like LEDs, are used in protected horticulture to achieve optimal light conditions for healthy plant growth and increased yield throughout the year. The effect of variation in wavelength is broad-ranging in plant physiology. Red light was found to increase flowering and biomass yield, while blue light increases compact growth and leaf expansion. UV and far-red light affect plant response, which includes stress resistance, flowering, and lengthening of stems. This will be achievable by manipulating the light spectrum and photoperiod to control the growth cycles of the plants, thereby enhancing crop quality through reduced energy consumption and efficient resource use. Advances in photobiology make it possible to create recipes of light for different crops, where output can be maximized under protected conditions. In addition, integration with the control of light with environmental variables, including temperature, humidity, and CO₂ concentration, leads to more sustainable and high-efficiency agricultural systems. In a nutshell, photobiology in protected horticulture helps optimize plant performance, contributes to food security, and supports sustainable agricultural practices in controlled environments.

Keywords: Artificial light, Environment, Light, photobiology, photosynthesis, protected horticulture.

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INTRODUCTION

Light influences plants in two primary ways on a biological level:

1. Light serves as an energy source for the metabolism of all plants and, consequently, all organisms that rely on plants for sustenance (herbivores).
2. Light serves as a “maestro,” providing cues about their environment and vital information that enables plants to predict changes in the seasons or between day and night.

The world is turning more and more to plant factories in response to global challenges such as unpredictable weather patterns, environmental degradation, water scarcity, the use of fossil fuels and plant biomass, and concerns about the stability and security of food supplies. Through a process known as photosynthesis, plants need light energy to grow and develop. Plant factories may be divided into two categories: those that utilize lamps as their only source of artificial light and those that use daylight in addition to or instead of additional artificial light [1].

The horticultural sector greatly desires the potential reduction in energy consumption that LED (Light-emitting diode) solutions may provide. However, because LEDs offer excellent spectrum control, LED lighting solutions have the most potential to change and enhance crop productivity. Many aspects of plant biology are influenced by light quality, and the photobiological mechanisms by which plants perceive and react to their light environment are well understood. Utilizing LED lighting to manipulate the light spectrum makes it possible to take advantage of this large body of information and develop better crop production systems. Optimal illumination patterns may improve plant quality, flavor, and nutritional value while improving yields and promoting the plants' health and quality. Plant resistance to pests and diseases can be increased, but direct interruption of the pest/pathogen relationship may additionally mitigate its effects [2].

The energy conversion efficiency of incident photons to chemical energy by leaves has been recognized for well over 50 years to be wavelength dependant. This is caused by a number of mechanisms that fall into two categories. First, because different leaf pigments have distinct absorptance spectra, the amount of incident irradiance that a leaf absorbs depends on its wavelength. Second, different wavelengths have different quantum yields for CO₂ fixation or O₂ evolution even on an absorbed light basis: the highest quantum yield is found in red light (600–640 nm), while blue and green light (400–570 nm) are much less effective in driving photosynthesis [3].

The science of photobiology examines how light and living things interact. The light that is typically of particular relevance for study is the ultraviolet, visible, and infrared energy that the sun sends to Earth. Research on the nature of how organisms see (photosynthesis), how light can be damaging (plant phototoxicity), and how light can produce energy (photobiology) is all included in the broad field of photobiology.

Understanding key essential biological processes—some of which humans cannot survive without—has been made possible due to substantial measures of photobiology. Photobiology is the branch of plant biology that describes how different light types may be distinguished by plants based on factors such as time, intensity, or spectrum. Our understanding of how to employ light to enhance plant growth is aided by the study of light's interactions with biomolecules—molecules found in living things. Molecules react with light at the nanoscopic level when they absorb photons, which are light energy particles, and enter an excited energy state. Molecular conformational changes or reactions with surrounding particles are the two ways that molecules recover energy stability. The earliest and maybe most significant application of photobiology is the process by which plants obtain energy from these two potential reactions [4].

In order to survive and adapt to the competition for sunlight, plants have developed the ability to sense shade through relative increases in the far-red (FR; 700–750 nm) photon flux density and reductions in the flux of all photons (intensity). Plant stem elongation and leaf expansion are regulated by the interaction between light intensity and FR photons. Horticultural crops are significantly impacted by these interactions. The phytochrome photo stationary state (PSS), sometimes called phytochrome photo-equilibrium, is defined as the ratio of active to total phytochrome (P_{fr}/P_{total}). It might be calculated using isolated phytochrome absorptivity data [5].

The spectral quality of supplemental lighting (SL) has a direct impact on crop output and nutritional quality in greenhouse crop cultivation. Through spectrum quality manipulation, greenhouse SL produced more secondary metabolites for commercial, medical, and culinary applications [6].

Improving the light environment and maximizing the efficient use of light energy by plants has become a more prominent concern in greenhouse tomato production. Artificial supplemental lighting improves the light conditions for plant canopies. Bifacial leaves are able to collect light on both their faces, and a review indicates they were much more effective at carbon fixation under the same level of illumination as one-faced leaves [7]. They examined alterations at the transcriptomic and proteomic levels in tomato leaves, given supplemental lighting

CHAPTER 8

Plant Metabolites

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Abstract: Plant metabolites are vital chemical compounds produced through metabolic pathways, playing key roles in the growth, development, and survival of plants. Primary metabolites, such as carbohydrates, proteins, lipids, and nucleic acids, are essential for cellular processes, including energy production, growth, and reproduction. These compounds serve as the foundational building blocks of life, supporting vital metabolic pathways like photosynthesis and respiration. In contrast, secondary metabolites, including alkaloids, phenols, flavonoids, and terpenoids, are not directly involved in growth but play specialized roles in defense, environmental adaptation, and interspecies interactions. Metabolomics, the comprehensive study of metabolites, has greatly expanded our understanding of these compounds. By analyzing the interconnected metabolic pathways, researchers can now explore how primary and secondary metabolites influence plant health, functionality, and adaptability. Secondary metabolites, in particular, have garnered attention for their bioactive properties, offering benefits to human health and industry. These compounds contribute to plant defense against herbivores and pathogens, and many possess antioxidant, anti-cancer, and antimicrobial properties beneficial for human use. Plants produce secondary metabolites through intricate biosynthetic pathways activated by environmental stresses, such as drought and salinity, to enhance survival. Their extraction, once limited to traditional methods, now benefits from advanced biotechnological techniques, such as tissue culture and metabolic engineering, offering higher yields and purity. As research into the biosynthetic pathways of these metabolites deepens, the potential for enhancing their production and applications continues to expand, offering sustainable solutions for health and industry.

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Keywords: Bioactive compounds, Biosynthetic pathway, Extraction, Functions, Plant metabolites, Primary metabolites, Secondary metabolites.

INTRODUCTION

Metabolism is a fundamental biological process that underlies the growth, development, and overall functioning of all living organisms [1]. It involves a series of chemical reactions within cells that convert nutrients into energy and the necessary building blocks for cellular activities. This complex network of reactions is essential for maintaining life, supporting growth, and enabling reproduction. Central to metabolism is the production of metabolites, which are small molecules that serve as intermediates and end products of metabolic pathways [2]. These metabolites play various roles, including energy production, regulation of cellular processes, and interaction with the environment [3]. Metabolites are integral to cellular functions and are crucial in maintaining the physiological balance within an organism [4].

Plant metabolites, both primary and secondary, are crucial for survival and adaptation, serving distinct roles in plant physiology [5]. Primary metabolites, including carbohydrates, proteins, lipids, and nucleic acids, are directly involved in essential processes like growth, development, and reproduction, forming the structural and functional foundation for cellular activities [6]. For example, glucose provides energy, while proteins and nucleic acids are vital for building cellular structures and transferring genetic information [7]. In contrast, secondary metabolites, such as alkaloids, flavonoids, terpenoids, and phenolics, are not directly tied to basic cellular functions but play specialized roles like defense against herbivores and pathogens, competition with other plants, and attraction of pollinators [8]. These compounds enhance a plant's adaptability and resilience, enabling survival in diverse environmental conditions despite not being essential for immediate survival [9].

The field of metabolomics has revolutionized our understanding of plant metabolites by enabling the comprehensive analysis of the metabolite profiles within biological systems. Metabolomics involves the systematic study of all metabolites in a cell, tissue, or organism, providing insights into the complex metabolic networks that regulate plant function [10]. Through metabolomics, researchers have gained a deeper understanding of how metabolites are interconnected and how they collectively influence the health and functionality of plants. This holistic approach has revealed the intricate balance between different metabolic pathways and has helped to identify their roles in plant biology [11].

Humans have long recognized the value of plant metabolites for various purposes, including food, medicine, and industrial applications. Since the earliest days of

civilization, people have utilized plants for their nutritional content as well as their therapeutic properties. Early humans distinguished between plants that could be eaten and those that could be used for medicinal purposes, laying the foundation for traditional medicine [12]. This traditional knowledge has been passed down through generations and continues to influence modern medicine and pharmacology [13]. The study of plant metabolites has led to the discovery of numerous drugs and therapeutic compounds, highlighting the enduring importance of plants in human society [14].

CLASSIFICATION OF PLANT METABOLITES

Plants are remarkable biochemical and biosynthetic factories that harness solar energy to produce a diverse array of organic compounds. These compounds, known as metabolites, play a vital role in various biological processes (Fig. 1). Plant metabolites are broadly classified into two categories, *viz.*, primary metabolites and secondary metabolites. These metabolites differ in their functions, characteristics, and significance to the plant's survival and interaction with its environment.

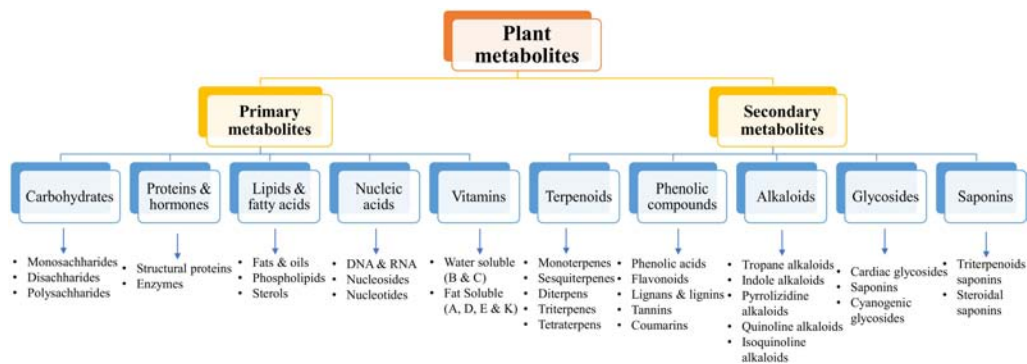


Fig. (1). Classification of plant metabolites.

PRIMARY METABOLITES

Primary metabolites are fundamental compounds integral to the basic metabolic processes that sustain life in all living organisms and plants. These metabolites are specifically involved in the essential functions of growth, development, and reproduction, making them indispensable for survival [14]. Found universally across all forms of life, primary metabolites participate in critical biochemical pathways such as cellular respiration, photosynthesis, and the synthesis of vital biomolecules [15]. Primary metabolites, including carbohydrates, proteins, lipids, nucleic acids, and certain vitamins, are essential for cellular structure and function. These metabolites are synthesized during the trophophase, underscoring

CHAPTER 9

Vertical Farming: Integrating Hydroponics, Aeroponics, and Aquaponics for a Sustainable Future

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Abstract: Vertical farming is emerging as a transformative solution to meet the growing global food demand, especially in urban environments. By integrating hydroponics, aeroponics, and aquaponics, vertical farming systems offer a sustainable approach to agricultural production, minimizing land use, water consumption, and reliance on chemical inputs. Hydroponics provides a soil-free method to cultivate plants with nutrient-rich water, while aeroponics allows for efficient root oxygenation by suspending plants in the air and misting the roots with nutrients. Aquaponics, meanwhile, combines aquaculture and hydroponics, creating a symbiotic ecosystem where fish waste provides natural fertilizer for plants, which in turn filter and purify the water for fish. This chapter explores how these systems work individually and in combination, highlighting their potential to reduce environmental impact while enhancing food security. Key challenges, including the high initial capital costs, energy demands, and technological complexity, are also discussed. Furthermore, we examine the role of automation, artificial intelligence, and renewable energy in optimizing vertical farming efficiency. Through case studies and comparative analysis, the chapter demonstrates the success of integrated vertical farming systems in various climates and settings. The chapter concludes by addressing how vertical farming can contribute to sustainable development goals, particularly in relation to climate resilience, urban agriculture, and sustainable food production systems, making it a vital innovation for the future of food security in a rapidly urbanizing world.

Keywords: Aeroponics, Aquaponics, Food security, Hydroponics, Sustainable agriculture, Vertical farming.

INTRODUCTION

Food security, a vital component of sustainable development, is an urgent global concern as nations grapple with difficulties emerging from growing urbanization

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[1 - 3]. The exponential development of urban populations exerts tremendous strains on conventional agricultural techniques, leading to worries about the ability to feed billions in the years to come [4]. As urban areas develop, the struggle for land rises, resulting in the conversion of productive agricultural land into urban infrastructure [5]. Moreover, urban locations sometimes confront constraints in resource availability, making it difficult to continue traditional agricultural operations [6 - 8]. These dynamics underline the critical need for new solutions to provide a robust and sustainable food supply for urban populations.

Vertical farming (VF) is emerging as a plausible solution to the challenges posed by urbanisation [9]. Unlike traditional farming, which relies on horizontal expansion, vertical farming capitalizes on vertical space within urban environments [10, 11]. This novel method entails the cultivation of crops in vertically piled layers or inclined surfaces, frequently within controlled environments such as warehouses, skyscrapers, or specially designed structures [12]. These structures with controlled environments allow for denser planting and precise management of nutrients and environmental factors, potentially resulting in increased crop yields per square meter [13]. Moreover, the absence of soil in VF systems minimises issues related to pests and weeds, potentially diminishing the necessity for pesticides [14]. VF systems also address the spatial constraints imposed by urbanisation by bringing food production closer to urban centres, guaranteeing a more efficient and sustainable use of available resources. This proximity allows for fresh produce to reach consumers more efficiently, reducing the carbon footprint associated with the transportation of fruits, vegetables, and other crops. This reduction in carbon emissions aligns with global sustainability goals, fostering environmentally friendly and resilient food supply chains [9, 11, 12].

Recently, producing sustainable food in cities using VF systems has gained a lot of interest and attention in many academic institutions and practical fields due to climate change, scarcity of irrigation water, and soil salinity, which has negatively affected food production worldwide [15, 16]. Consequently, this practice is regarded as a crop-production strategy that is climate-resilient and can be helpful in future climate instabilities. This cultivation system offers several benefits for food and nutrition security, including increased production in resource-limited areas, reduced reliance on unpredictable weather patterns, enhanced access to fresh produce in urban areas, and more sustainable production practices with diminished environmental impact [17 - 19]. Therefore, this chapter aims to evaluate the feasibility of integrating different types of VF systems for sustainable agriculture during these difficult times when the globe is undergoing a climate crisis.

TYPES OF VERTICAL FARMING SYSTEM

It is crucial to recognise that vertical farming is soilless agriculture. VF systems are of various forms, such as aeroponics, hydroponics, and aquaponics, or one or more of these combinations, as illustrated in Fig. (1).

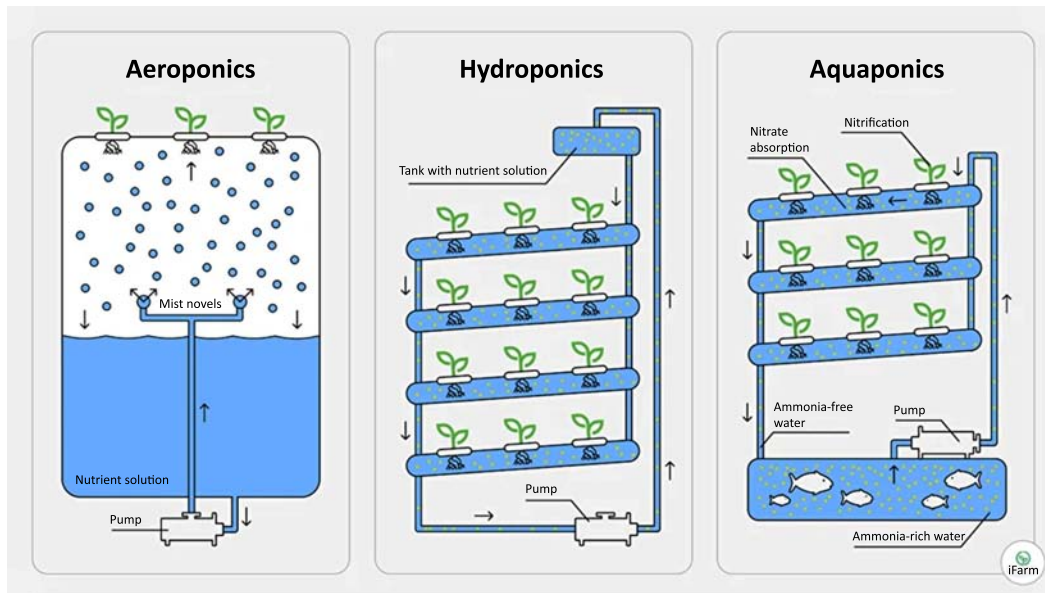


Fig. (1). Most common vertical farm systems.
(Source: <https://ifarm.fi/blog/vertical-farming-systems>).

Aeroponics

Aeroponics (Fig. 1A) is a sophisticated kind of hydroponics that entails cultivating plants in a mist environment devoid of soil or other aggregate media [20]. This new growing technique enables plant roots to directly absorb nutrients from a thin mist, optimising oxygen exposure and nutrient assimilation [21]. Enhanced air exposure facilitates fast root growth and provides superior control over the plant's surroundings. Aeroponic systems may result in accelerated growth rates, increased yields, and enhanced water efficiency compared to conventional farming techniques [20, 21]. Furthermore, because aeroponics is independent of soil, it mitigates the threat of soil-borne pathogens and pests, making it an optimal solution for space-constrained urban agriculture and possibly for extraterrestrial farming [22, 23]. The components of aeroponics include an aeroponic chamber, misting nozzles, a nutrient reservoir, a submersible pump, a cycle timer, root supports, a pressure gauge, a drainage system, an air filtering system, a lighting system, and environmental controls [24].

Protected Cultivation of Horticultural Crops: Fruits

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Abstract: India is the world's second-largest producer of fruit crops, but due to low land holdings, rain-fed farming, inappropriate use of natural resources, and excessive reliance on chemical pesticides and fertilizers, India continues to lag behind in terms of fruit yield and quality for export. These chemicals also pollute the environment, and because of residue buildup, fruits grown with pesticides are not recommended for export. Fruit crops are most popular among horticultural crops due to being an important source of minerals, vitamins, and antioxidants. Among horticultural crops, fruit crops occupy an area of nearly 67.5 million hectares worldwide. Key constraints faced in conventional fruit cultivation, such as pest attacks, climate variability, soil degradation, *etc.*, decrease the yield of fruit crops. To produce high-quality fruits, one must opt for protected cultivation in order to overcome the difficulties posed by the climate. Additionally, it offers an excellent benefit-to-cost ratio along with yield and quality improvement. A more scientific approach is necessary to achieve improved quality, which is challenging to accomplish using the conventional methods of agriculture. Hence, the current book chapter addresses different protected structures, such as greenhouses, net houses, polytunnels, *etc.*, for fruit cultivation. Appropriate soil, water, and nutrient management with adequate plant protection in protected structures increases the yield and quality of fruit crops. The chapter will also explore the role of different modern technologies used in controlled cultivation, such as hydroponics, aeroponics, aquaponics, AI, and robotics, highlighting the importance and constraints of protected cultivation for fruit crops.

Keywords: Deciduous plants, Evergreen plants, Fruit crops, Modern technology, Protected structures, Sustainability, Yield enhancement.

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INTRODUCTION

Fruit crops are important sources of vitamins, minerals, and antioxidants, which have a vital role in human nutrition. Therefore, fruit crops are considered “protective foods”. Worldwide, fruit crops are cultivated in a 67.5 m/ha area. In conventional fruit cultivation, many constraints are faced by farmers, such as soil degradation, extreme temperature or cold, heavy rainfall, and pest and disease attacks, which are responsible for the lower yield and quality of the fruit crops. Protected cultivation of fruit crops enhances yield and quality by protecting plants from adverse weather, pests, and diseases, thus extending the growing season and ensuring more consistent production. It also allows for better control of growing conditions, leading to improved fruit quality. Besides these, protected cultivation also supplies the off-season production of fruit crops, which can help farmers fetch higher income from their produce. In this type of cultivation, different protected structures are used in which controlled climatic conditions can be provided.

Definition of Protected Structures

Protected structures can be defined as “structures that create a controlled environment that mitigates the impacts of unpredictable weather and other external factors that increase the quality of fruit production”. For example, greenhouses, polytunnels, shade nets, *etc.*

Brief History and Present Status of Protected Cultivation

The first record of crop cultivation utilizing protected structures dates back to 37 CE in Rome [1]. During cold periods, plants on carts were moved into protective shelters known as Specularia. Ondol is a traditional underfloor heating system used to nurture mandarin (citrus) trees till they produce their fruits.

During the 17th and 18th centuries, France utilized structures known as Orangeries to shield fruit trees from cold weather [2]. These were tall masonry buildings with expansive glass windows on the southern side to maximize sunlight. Fruit trees, such as oranges, grown in pots, were brought into these buildings during winter to protect them from the cold. By the 19th century, Europe saw the construction of large glasshouse conservatories designed to cultivate exotic tropical plants brought in from other regions. Contemporary commercial greenhouses differ significantly from the Orangeries of the 18th century and the glasshouses of the 19th century. Modern greenhouse designs have evolved primarily to accommodate local climatic conditions. During the 20th century, many large-scale greenhouses were established in the Westland region of the Netherlands. In China, protected cultivation began in the 1990s, and today, the area dedicated to this method spans

approximately 0.5 million hectares, with 90% of this space used for growing vegetables [3].

It is projected that the area allocated for protected cultivation will grow to about 84.2% between 2013 and 2017. In China, a variety of fruits, such as strawberries, grapes, peaches, nectarines, flat peaches, apricots, cherries, plums, and citrus fruits, have thrived under protected cultivation. Of these, strawberries cover the largest area, representing roughly 70% of the total production, followed by grapes, peaches, and nectarines.

Currently, greenhouse cultivation in China exceeds 2.5 million hectares, with 90% of this area dedicated to vegetable production [4]. Israel has also enhanced its agricultural sector through protected cultivation, leveraging greenhouse techniques to produce high-quality vegetables, flowers, and fruits in arid regions where water is scarce. In the United States, greenhouse cultivation covers thousands of acres, with even larger areas found in England and the Netherlands. India is now collaborating with international partners like Israel to adopt protected cultivation technologies, which is expected to significantly boost agricultural productivity.

Necessity of Protected Cultivation for Fruit Crops

The population of the world is estimated by the UN to be 7.7 billion at the moment, growing to 8.6 billion in 2030 and 9.8 billion in 2050. By 2050, 120% more water and 42% more farmland will be needed to feed the world's population. Traditional outdoor agriculture is difficult to maintain when additional factors like manpower shortages and water limits are taken into account. According to a study [5], one of the greatest ways to boost agricultural and food production is through protected agriculture in greenhouses.

- **Climate Control:** It provides a controlled environment that shields fruit plants from extreme weather conditions, such as frost, excessive heat, and heavy rainfall, which can damage crops and reduce yields.
- **Pest and Disease Management:** Enclosing plants in protective structures minimizes exposure to pests and diseases, leading to healthier plants and higher-quality fruit.
- **Extended Growing Season:** It enables year-round or off-season production, allowing farmers to grow fruits outside their natural growing season and improve market availability.
- **Enhanced Quality:** It helps to produce fruit with fewer blemishes and better overall quality by offering consistent growing conditions and protecting plants from environmental stressors.

CHAPTER 11

Protected Cultivation of Horticultural Crops: Vegetables and Flowers

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Abstract: Agriculture and other related sectors have a significant impact on the Indian economy. The Green Revolution introduced new biotic and abiotic stresses, posing significant challenges. Protected cultivation minimizes stress by providing a regulated environment. The growing demand for food requires us to consider protected farming. Greenhouses are the most effective solution for protected horticulture. Protected production of high-value vegetables has shown remarkable promise over the past decade. Protected cultivation offers hitherto untapped opportunities in agriculture with the advancement of technology and a liberalized economy. These technologies benefit both large-scale producers and those with smaller landholdings, as increased production levels remain economically relevant to agriculture. Protected cultivation is a precise, progressive, and parallel approach to agriculture that considers technological aspects, grower needs, and market economics. Flowers are becoming popular as a means of celebrating special occasions. India's protected flower industry has led to an increase in commercial flower exports. To meet the demand, floriculture crops like roses, gerbera, carnations, lilies, *etc.*, are grown in protected structures. Protected farming is a crop cultivation technique that controls the plant's microclimate for optimal growth.

Keywords: Controlled environment, Flowers, Greenhouse, High-tech horticulture, Hydroponics, Protected cultivation, Soilless cultivation, Vegetables.

INTRODUCTION

Greenhouse technology utilizes structures and equipment to provide a controlled environment for agricultural production. Vegetables and flowers can be protected from factors like wind, rain, and pests or grow optimally under specified circum-

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tances. Greenhouses may grow many crops, such as vegetables, fruits, flowers, and herbs [1]. Greenhouse technology protects crops from severe external circumstances, ensuring optimal development throughout the year. Protected farming, also known as controlled environment agriculture (CEA), is extremely productive, conserving water and land while simultaneously protecting the environment [2]. The method includes cultivating horticultural crops in a controlled environment and manipulating elements like temperature, humidity, light, soil, water, and fertilizers to maximize crop production and provide a consistent supply even during the off-season.

Growing vegetables in greenhouses requires meticulous planning and many phases to ensure success. Greenhouse design varies by geography, including deserts, tropics, and temperate regions [2]. Glasshouses are favored in temperate climates, whereas greenhouses provide a 'shading effect' and 'windbreak effect' in subtropical and tropical areas. Rain shelters are commonly used in wet tropical locations to prevent floods [3]. Vegetable crops frequently require protection from several weather situations, such as against variable temperatures, sun radiation, severe rain, hail, and high winds. Choosing the ideal location for a greenhouse is crucial.

Greenhouses should be located away from industrial and densely inhabited regions. Priority is given to leveled land with optimal lighting conditions. When building a greenhouse on a slope, ensure that surface runoff is channeled away from the structure. Proper drainage to a lower region is required for the site [4]. Drip irrigation is widely used for the supplement of water. Grafting vegetable seedlings is a unique horticultural technique for combating soil-borne illnesses and nematodes, as well as increasing plant vitality in challenging environments (Table 1). The method of grafting involves selecting rootstock and scion species, creating a graft union by physical manipulation, mending the union, and acclimating the grafted plant [5]. In 1993, the first commercial robot for grafting cucumber seedlings was created [6]. Semi- and completely automated grafting robots for plugs can be created by combining adhesive and grafting plates.

Table 1. Different grafting methods followed in vegetables [5].

Crop	Grafting Method
Cucumber	Tongue Approach, Splice
Watermelon	Hole Insertion, Tongue Approach
Tomato	Pin Grafting, Tongue Approach
Eggplant	Cleft, Pin Grafting
Pepper	Splice

India is the world's second-largest flower grower behind China and ranks 14th in terms of floriculture exports [7]. Urbanization and higher disposable incomes have led to increased demand for floriculture goods [8]. Flowers are becoming popular as a means of celebrating special occasions. India's protected flower industry has led to an increase in commercial flower exports. Floriculture crops have more potential per unit area than other field crops, making it a more profitable company. Floricultural items for export include cut flowers, pot plants, cut foliage, seeds, bulbs, tubers, rooted cuttings, and dried flowers/leaves. The demand for cut flowers is growing both domestically and internationally. Roses, carnations, chrysanthemums, gerberas, gladiolus, gypsophila, nerine, orchids, anthurium, tulips, and lilies are popular cut flowers in the worldwide market. To fulfil demand, floriculture crops such as roses, gerberas, carnations, and lilies are cultivated in greenhouses [9].

As agricultural technology advances, new protected agriculture techniques emerge. Different types of protected structures are adopted based on India's diverse agroclimatic zone and its availability of resources. Greenhouses, plastic houses, high-polytunnels, low-polytunnels, cloth homes, net houses, shade houses, *etc.*, are the types of protected cultivation. A low-cost greenhouse method was created to produce high-quality flowers in mountainous areas, including J&K, Himachal Pradesh, Uttaranchal, and North-Eastern states. These structures are currently professionally employed to export high-quality flowers from Maharashtra and Karnataka. Protected horticulture is effective for growing high-quality crops such as roses, gerbera, carnations, and lilies. Flower production in enclosed structures is increasingly employed in commercial agriculture to improve quality and profitability. Low-cost polyhouses have the potential to expand protected agricultural areas. Farmers can sell their goods to nearby markets [10].

Soil Based Cultivation

Growing vegetables in greenhouses often entails planting directly in well-drained soil. The same crop over a period of time may completely damage the soil structure in the greenhouse. Maintaining soil structure requires proper attention. Soil preparation includes procedures such as cleanliness, solarization, mulching, and fumigation. Solarization has multiple benefits, including reducing soil-borne pathogens through soil heating, increasing plant growth response, controlling weeds and insect pests, and serving as a bioremediation tool for pesticide-polluted soils [11, 12]. Combining solarization with other control measures can provide additional benefits. Incorporating manure, compost, and other organic amendments improves soil structure and fertility, increasing microbial activity and nitrogen uptake by plants. This also reduces soil-borne illnesses, leading to

CHAPTER 12

Protected Cultivation of Horticultural Crops: Medicinal and Aromatic Plants (MAPs)

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Abstract: Aromatic and medicinal plants play a significant role in the social, medical, and spiritual existences of India's rural community. The livelihoods of the rural population benefited greatly from medicinal plants. Medicinal and aromatic plants (MAPs) are essential components of the world's ecological heritage, environment, and biodiversity. From ancient times, medicinal and aromatic plants have been used to treat a wide range of ailments in conventional medical systems. They are also used as sources of natural dye, fat, essential oil, bio-pesticide, resin, protein, vitamin, condiment, spice, timber, fiber, and other useful materials, as well as for therapeutic, fragrance, and flavoring products in the pharmaceutical and cosmetic industries. Despite the fact that agriculture has long been the foundation of India's economy, our observation over the last 50 years with protected cultivation suggests a link between agricultural practices and economic well-being. Controlled environment cultivation provides an effective way to manage medicinal and aromatic plants where biosynthesis of bioactive compounds is the determining factor of crude drug or raw material for which protected cultivation and agro-input management is a decisive factor. Hence, the current book chapter illustrates the importance of a controlled environment for the cultivation of selected industrially important medicinal and aromatic plants in order to have a sustainable future.

Keywords: Agrotechnology, Aromatic plants, Cultivation practices, Economy, Industry, Medicinal plants, Protected cultivation, Propagation, Sustainability.

INTRODUCTION

In order to produce crops in regulated or partially controlled climates for commercial purposes, protected agriculture techniques are commonly employed. Their contribution to boosting agricultural productivity and output might be

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crucial in emerging nations such as India. In India, summer (April to June) is characterized by high temperatures, low humidity, and paucity of water. Producing plants is quite challenging under these circumstances [1]. Low-density polyethylene (LDPE) plastic sheets are frequently used in agriculture as mulch for soil and as covers for greenhouses and low tunnels, with the goal of improving the produce's quality and production [2]. The plastic covering of greenhouses serves the dual purposes of protecting plants from airborne contaminants and raising the temperature within the greenhouse, extending the goods' shelf life [3].

Production in agriculture and horticulture has reached its maximum yields, and this cannot be sustained without triggering more negative externalities or increasing costs. Over the last few centuries, there have been numerous examples of the ecological fragility of severe, homogenous monocultures. Integration in natural patterns and customs and the introduction of digital and circular systems in farm management are the characteristics of the Fourth Farm Revolution [4]. Regenerative agriculture must become a standard in sustainable agriculture owing to the numerous critical challenges that the future of land utilization will face in order to safeguard future generations [5, 6]. The food, cosmetics, and pharmaceutical sectors have an increasing need for medical plant-based products, and this pattern is predicted to expand. In industrialized nations, the ratio of wild-growing to cultivated (Medicinal and Aromatic Plants) MAPs is steadily changing in favor of cultivation [7].

Herbs with medicinal properties are excellent tools for treating a range of ailments. Environmental requirements, vegetation cycles, and bioactive compounds vary greatly between the species. Harvesting them from wild vegetation puts biodiversity at risk. Furthermore, there is a great deal of unpredictability in terms of quantity and quality due to weather volatility and future possibilities in light of climate change [8, 9].

One way to ensure the consistent and sustainable growth of aromatic and medicinal plants is through cultivation in protected areas. Variations in temperature, light, humidity, and other climatic factors can regulate plant development and the buildup of bioactive substances, allowing for the year-round production of consistent harvests [10]. The targeted bioactive compounds are accumulated by medicinal plants through secondary metabolism, which is brought on by factors such as temperature, light, nutrition, pests, and water availability. The harvest period and the proportion of blooms, buds, and flowers that reach anthesis can affect the plant's bioactive components. It is crucial to distinguish and investigate the stress inputs in order to comprehend how plants respond [11].

There are several benefits to soilless cultivation, which include increased yields with less chemical input and water reductions of up to 70% [12]. Farmers have the ability to control irrigation and nutrition, which results in optimal conditions for plant growth. Studies on medicinal plants grown in hydroponic systems are scarce. With this method, the cultivation of medicinal plants may be successfully advanced by precisely controlling stress to produce high bioactive material accumulation in the plants [13].

The first proof that Neanderthal people used medicinal herbs was presented by Hardy *et al.* [14]. The main source of therapeutic agents back then was medicinal and aromatic plants, which are still widely employed in both conventional and contemporary healthcare systems. According to a recent WHO survey, 48% of people in Australia, 70% of people in Canada, and 75% of people in France have utilized plant-based medicine at least once. It is possible to distinguish easily between medicinal and spice plants.

Aromatic plants, which include roots, wood, bark, stems, leaves, flowers, and fruits, exude gum, balsam, oleoresin, and other odorous volatile chemicals in one or more parts. The unique aroma is the result of several intricate chemical reactions. Essential oils and perfumes are interchangeable terms since the essence or active ingredients of the plants are reflected in these oily scents. Products having a low volume and high concentration are known as critical oils. Out of over 1500 species of aromatic plants, information on the chemistry and characteristics of only roughly 500 species' essential oils is known [15]. Ever since, the realm of essential oils has grown beyond its initial definition to encompass a vast array of uses in flavors, mouthwash, cigarettes, medications, and almost every aspect of human endeavor. Approximately 17% of the global flavor and fragrance industry is made up of essential oils [16].

Controlled environment cultivation provides an effective way to manage medicinal and aromatic plants where biosynthesis of bioactive compounds is the determining factor of crude drug or raw material for which protected cultivation and agro-input management is a decisive factor.

Important Medicinal Plants Under Controlled Environment

Acorus calamus

Acorus calamus Linn., also known as “sweet flag,” is a species of flowering plant that contains hallucinogenic components. It is native to parts of India's Himalayas and grows readily and indiscriminately in the wild. The leaves of *A. calamus* have 0.5–2 cm width and curved or undulating edges [17]. The branching, fragrant rhizomes have a thickness of 2 to 2.5 cm. *A. calamus* rarely produces flowers, but

CHAPTER 13

Weed Management in Controlled Environment Horticulture

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Abstract: Sustaining a weed-free greenhouse is essential for growing high-quality and marketable greenhouse crops. Weeds detract from crops' marketability by competing with them for nutrients, light, and water. Weed growth is basically less of an issue in nursery crops than it is in floriculture crops. This is so because the majority of crops grown in floriculture are grown on a premium medium that has low weed seed contamination. Nevertheless, they still may be an issue, especially in structures with soil, gravel, or ground cloth floors. Sometimes, organic stuff seeps into the gravel, providing the perfect environment for germination. Furthermore, weeds may grow up through the rips, tears, and worn areas of the ground fabric. It is critical to regularly search areas for weeds. Weeds do not immediately hinder plant development, despite the fact that they can harbor pests and diseases, including aphids, whiteflies, thrips, and mites, beneath seats and on sidewalks. For efficient and reasonably priced weed control, a high-quality integrated pest management program will include both natural and chemical methods.

Keywords: Floriculture, Greenhouse, Herbicide, IPM, Horticulture, Nursery, Nutrients, Preemergence, Postemergence, Weeds.

INTRODUCTION

The maxim “start clean - stay clean” should apply to weeds as well as to nursery managers. This is specifically true for people who cultivate perennial herbs. Resolving weeds is a continuous problem in greenhouses used for retail and wholesale. Producing superior greenhouse vegetables requires keeping the growing environment free of weeds. Just by consistently implementing suitable

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weed control strategies in conjunction with the necessary control measures, insects and diseases can be reduced to a minimum. Persistent issues in greenhouses include weeds like hairy bittercress (*Cardamine hirsuta*), prostrate spurge (*Euphorbia humistrata*), chickweed (*Stellaria medium*), and creeping wood sorrel (*Oxalis corniculata*) [1]. These weeds are annual and reproduce mostly by seed, producing many generations periodically. Weeds must be pulled out before they blossom and start to seed. Although postemergence herbicides work well against most overgrown grassy weeds, there are not many herbicides on the market for managing them. In addition, weed killers that are authorized for use with herbaceous ornamentals are safe for a lot of ornamentals and effectively suppress weeds. Therefore, to effectively control weeds in nurseries, a comprehensive program comprising exclusion, sanitation, preemergence herbicides, some postemergence herbicides, and hand weeding will prove necessary [1].

Weeds may compete with good crop plants for nutrients, water, and light. Additionally, weeds detract from the crops' aesthetic value and give off a bad impression to onlookers. Along with aphids, whiteflies, thrips, mites, slugs, and illnesses, weeds are a major source of these pests. Weeds with slow growth contribute to the preservation of moisture, which creates an ideal habitat for shore flies and fungus gnats. Many common greenhouse weeds may be reservoirs of impatiens necrotic spot virus (INSV) while not showing any visible symptoms.

A number of popular greenhouse weeds, including tomato spotted wilt virus (TSWV) and impatiens necrotic spot virus (INSV), can infect a plant while exhibiting little to no obvious symptoms, including chickweed, oxalis, bittercress, dandelion, and ground ivy. The virus can then spread to greenhouse crops that are vulnerable to thrips. Weed populations can be efficiently managed with the use of an integrated weed management program. This covers the use of mechanical controls (hand pulling), physical controls (physical barriers), cultural controls (prevention and cleanliness), and the targeted application of chemical controls (herbicides). A 10-20 foot weed-free barrier surrounding the greenhouse can be implemented to stop weed seeds from being blown inside. To stop weeds from growing, a geotextile cloth can be used both inside and outside the greenhouse. Shed weeds using herbicides or clip them with a mower. When applying herbicide, greenhouse vents can be shut off to avoid herbicide drifting inside and harming delicate crops.

How They Arrive?

Weeds and their seeds are carried into the greenhouse by contaminated plant matter, people, animals, tools, and equipment. Drastic irrigation (chickweed),

wind (dandelion, horseweed, groundsel), and natural seed motion (wood sorrel, bittercress) are some of the ways that seeds can be dispersed. Annual weeds reproduce mostly *via* seed, producing multiple generations annually. Weeds, once allowed to flower in the greenhouse, yield copious amounts of seed; some, like bittercress and wood sorrel, can shoot seeds up to 12 feet into the greenhouse. In order to effectively control weeds, it is necessary to combine postemergence herbicides, weed fabric, hand weeding, and preventative measures.

Prevention

Prevention and sanitation are the first steps to managing weeds.

- Vents and other openings make it simple for weed seeds to be blown inside the greenhouse.
- It is possible for weeds and their seeds to enter the greenhouse through contaminated plant material, tools, and equipment.
- In addition to people and animals, the wind and irrigation water can also move seeds in the soil. Many generations of annual weeds, including hairy bittercress, prostrate spurge, creeping wood sorrel, and common chickweed, reproduce mostly by seed.

Sanitation

- Use “clean” plant materials, sterile media, and weed control techniques to keep rhizomes and seeds of weeds out of the greenhouse.
- Clean up spilled growing media, which provides an ideal environment for the germination of weed seeds.
- Screen vents and other openings to help keep insects and wind-blown seeds out of the area.
- Identify the weeds' life cycle (annual, biennial, or perennial), kind (grass or broadleaf), and location when doing scouting. See the UMass Extension Weed Herbarium or listed references listed for help in identification.
- Eliminate weeds from benches, floors, and greenhouse pots before they flower and seed. For instance, a single bittercress plant can yield 5000 seeds, which can spread up to 9 feet from the plant and germinate in as little as 5 days! Both creeping and yellow woodsorrels forcibly eject their seeds all over a greenhouse.

Physical Barriers

- Using weed block fabric or another physical barrier can help reduce the number of weeds that grow on greenhouse floors.

CHAPTER 14

Pest and Disease Management in Controlled Environment Horticulture

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Abstract: The cultivation of crops in controlled environments (CE) has progressed from laboratories, greenhouses, and screenhouses to advanced technologies such as aquaculture and hydroponics. Various biotic and abiotic factors are regulated and optimized in these systems to benefit the cultivated plants. The use of CE for growing food originated from the need to provide more quality and quantity of food to accommodate the increasing world population. Pests and diseases significantly hinder crop productivity, posing a challenge to the objectives of CE. Common pests of CE include but are not limited to aphids, thrips, whiteflies, caterpillars, botrytis (grey mold), downy mildew, and powdery mildew. The current book chapter addresses eco-friendly solutions to reduce pest populations and prevent disease infections. It will cover early warning systems and regular surveillance of pest species in CE. Additionally, it will examine integrated pest and disease management strategies to control pests and diseases in CE. This chapter will also explore advanced technologies such as biotechnology, AI, machine learning, and robotics, representing the future of farming. Finally, the book will propose future pest and disease management directions in CE.

Keywords: Biological, Biocontrol, Cultural, Cultivation, Diseases, Endophytes, Fungus, IPM, Pest, Population.

INTRODUCTION

Controlled Environment Horticulture (CEH) refers to the cultivation of plants in highly controlled and optimized indoor environments, where factors such as

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temperature, humidity, light, carbon dioxide, and sometimes even root-zone conditions are meticulously regulated. This type of horticulture encompasses various forms, including greenhouses, indoor vertical farms, hydroponics, and aeroponics. While CEH offers immense potential for year-round production, enhanced plant growth, and improved resource efficiency, it also presents unique challenges in terms of pest and disease management. These challenges necessitate tailored strategies to protect plants from pathogens and pests, which can thrive in the optimal microclimates created for plant production [1, 2]. Controlled Environment Horticulture is typically defined as the production of crops within structures that allow growers to manipulate the growing environment to optimize plant growth and yield [3]. Unlike traditional outdoor cultivation, where plants are exposed to varying weather conditions, CEH systems offer the ability to precisely control key environmental parameters. According to Kozai [4], CEH integrates cutting-edge technologies such as LED lighting, automated climate control, and hydroponic or aeroponic nutrient delivery systems. This system allows growers to enhance both crop yield and quality, and it is particularly advantageous for high-value crops like leafy greens, herbs, and medicinal plants.

While CEH provides several advantages, including extended growing seasons, higher productivity per unit area, and reduced water use [5], these controlled environments also pose significant risks for the proliferation of pests and diseases. Pathogens and insects can thrive in the consistently warm, humid, and light-optimized conditions of CEH. Therefore, effective pest and disease management is essential for maintaining crop health and ensuring that CEH systems deliver on their promise of sustainable, high-efficiency agriculture.

Importance of Pest and Disease Management in CEH

Pest and disease management is critical in CEH due to the unique environment it creates, which can favor the rapid proliferation of pathogens if not properly managed. Unlike open-field environments where pests and diseases are influenced by natural fluctuations in temperature, humidity, and wind, the controlled conditions in CEH often present ideal conditions for the survival and reproduction of various plant pathogens, including fungi, bacteria, viruses, and insects [6]. Without natural deterrents, such as environmental stress or predatory organisms, pathogens and pests can rapidly spread and cause devastating crop losses if unchecked [7].

Closed Environments and Pest Proliferation

The controlled nature of CEH systems limits natural predators and environmental factors that traditionally help manage pest populations in open fields. Buitenhuis [8] argues that the absence of these natural controls in CEH necessitates

alternative strategies, such as the use of biological controls, chemical treatments, and mechanical exclusion. However, even these solutions require careful implementation, as CEH systems often involve high plant densities and close proximity, which can allow pests such as aphids, spider mites, and whiteflies to rapidly multiply and spread between plants [7].

For example, *Trialeurodes vaporariorum*, commonly known as the greenhouse whitefly, is a significant pest in CEH systems. Its life cycle is often shortened in the stable, warm environments of greenhouses, allowing for faster reproduction and an increased potential for crop damage [9]. Other pests, like thrips and spider mites, also benefit from the lack of wind and predators in these closed environments, further complicating pest management [8].

Insect Pests in Controlled Environment Horticulture (CEH)

In controlled environment horticulture (CEH), the enclosed and optimized conditions can promote rapid reproduction and spread of insect pests. Two of the most significant pests in CEH are aphids, whiteflies, and thrips. Aphids (Aphididae) are soft-bodied insects that feed on a wide variety of plants by piercing plant tissues and sucking sap. In CEH, aphids pose a serious threat to crops due to the stable and favorable environment that promotes their proliferation (Table 1).

Table 1. Common insect and mite pests in controlled environment horticulture: Crops, damage, and management strategies.

Crop	Insect Pests	Mite Pests	Damage	Management Strategies	References
Tomato	Aphids (<i>Aphis gossypii</i>)	Spider Mites (<i>Tetranychus urticae</i>)	Leaf distortion, sap sucking, stippling	Biological control (e.g., lady beetles, predatory mites), insecticidal soaps	[22]
Tomato	Whiteflies (<i>Bemisia tabaci</i>)	Broad mites (<i>polyphagotarsonemus latus</i>)	Leaf yellowing, stunted growth, honeydew secretion	Sticky traps, <i>Encarsia formosa</i> , insecticidal soap	[23]
Cucumber	Thrips (<i>Frankliniella occidentalis</i>)	Thrips and eriophyid mites	Silvering of leaves, virus transmission	Predatory mites (<i>Amblyseius cucumeris</i>), blue sticky traps	[24]
Cucumber	Aphids (<i>Myzus persicae</i>)	Spider Mites (<i>Tetranychus urticae</i>)	Sap sucking, leaf curling, chlorotic spots	Beneficial insects, insecticidal soap, miticides	[25]

CHAPTER 15**Economics and Market of Controlled Environment Horticulture (CEH)**

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Abstract: Controlled Environment Horticulture (CEH) is reshaping modern agriculture through its focus on sustainable food production and efficient resource management. This chapter provides an extensive exploration of the economic and market dynamics of CEH, underscoring its diverse revenue streams, including both fresh produce and value-added products. Despite its potential, CEH is hindered by substantial initial capital requirements and high operational costs, presenting significant entry barriers. Government policies, subsidies, and financial incentives are critical in alleviating these financial challenges, promoting innovation, and supporting sector expansion. The market is increasingly influenced by growing consumer demand for organic and premium products, especially in urban centers with heightened demand for such offerings. In this competitive environment, success relies on strategic approaches such as differentiation, cost leadership, and technological innovation. A deep understanding of these economic factors is essential for overcoming challenges and capitalizing on opportunities, ensuring CEH's scalability and long-term viability in addressing global agricultural demands.

Keywords: Controlled environment, Cost analysis, Economics, Finance, Global market, Horticulture, Regulations, Revenue, Trade, Value-added products.

INTRODUCTION

Controlled Environment Horticulture (CEH) represents a cutting-edge agricultural method that leverages technological advancements to create optimal growing conditions for plants. By precisely managing variables such as light, temperature, humidity, and carbon dioxide, CEH enables the continuous production of high-quality crops throughout the year. This approach is crucial for tackling global challenges such as food security, climate change, and the scarcity of arable land.

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However, the economic factors associated with CEH, such as costs, profitability, and market trends, are vital for ensuring its long-term viability and growth. CEH includes a variety of agricultural systems, such as greenhouses, vertical farms, hydroponics, and aquaponics [1]. These systems are engineered to maintain ideal conditions for plant growth, regardless of external environmental factors, ensuring reliable and efficient production.

The evolution of CEH has seen a shift from traditional greenhouses to advanced indoor farming technologies. While early greenhouses were designed mainly to extend the growing season, modern CEH incorporates high-tech elements like sensors, artificial lighting, and automated irrigation systems [2]. These innovations enable precise resource management and allow for crop cultivation in urban and resource-constrained areas.

CEH plays a crucial role in modern agriculture by addressing several key issues. It promotes sustainable food production, reduces food transportation distances, and mitigates the impact of climate-related crop failures [3]. By supplying fresh, local produce to urban centers, CEH not only minimizes the carbon footprint associated with food transport but also strengthens food security [4].

ECONOMIC PRINCIPLES IN CEH

Cost Structure of CEH

Controlled Environment Horticulture (CEH) requires significant capital investment, primarily for infrastructure like greenhouses or vertical farming units and advanced technology such as climate control systems, automated irrigation, and high-efficiency lighting [5]. These upfront costs offer long-term benefits by improving yields, reducing resource usage, and enhancing efficiency. Operational costs, including energy, labor, water, and nutrient inputs, also play a key role, with energy being a major expense due to artificial lighting and climate control needs [6]. Labor costs can be mitigated through automation, while water and nutrient inputs are generally lower than in traditional farming but require efficient management [7]. Regular maintenance ensures smooth operations, and accounting for depreciation is essential, as equipment will need upgrades or replacement over time to maintain system efficiency and profitability.

Revenue Streams in CEH

The primary revenue stream for CEH operators is the sale of fresh produce, ornamental plants, and specialty crops [8]. CEH products, which often include high-quality, locally grown fruits, vegetables, and herbs, can command premium prices, particularly in urban markets where there is strong demand for fresh,

organic, and sustainably produced goods [9]. This revenue stream is critical for the financial success of CEH ventures.

In addition to selling fresh produce, CEH operations can diversify their revenue through value-added products. These might include processed foods, herbal extracts, and cosmetics [10]. By creating these additional products, CEH operations can enhance profitability and reduce reliance on a single revenue source, thereby spreading risk and improving financial stability.

Alternative Revenue: Agritourism, Educational Programs

In addition to traditional revenue sources, many Controlled Environment Horticulture (CEH) operations are increasingly turning to alternative revenue streams such as agritourism and educational programs. These innovative approaches offer diverse income opportunities and enhance the overall value proposition of CEH ventures [11]. These activities can include facility tours, workshops, and demonstrations on sustainable farming practices. Agritourism not only provides additional income but also promotes public awareness and engagement with sustainable agriculture, adding value beyond traditional product sales [12]. By showcasing the technology and methods used in CEH, agritourism helps demystify the complexities of modern agriculture and promotes community involvement.

PROFITABILITY AND MARKET DYNAMICS

Profitability and Break-Even Analysis

Assessing profitability in Controlled Environment Horticulture (CEH) involves using economic models such as cost-benefit analysis and break-even analysis. Cost-benefit analysis compares total costs with expected revenues to determine financial viability, while break-even analysis identifies the minimum production required to cover costs [13]. Sensitivity analysis further examines how changes in variables like energy and labor affect profitability. Together, these models help CEH operators manage financial risks, make informed decisions, and optimize their financial strategies for long-term success [14].

Factors Influencing Profitability in CEH

Profitability in CEH is influenced by factors such as energy efficiency, technological innovation, and market demand. Effective energy management and the adoption of cutting-edge technologies can significantly enhance production efficiency and reduce costs. Additionally, meeting consumer demand for high-

CHAPTER 16

Current Scenario and Future Prospects of Controlled Environment Horticulture

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Abstract: Controlled Environment Horticulture (CEH) offers a transformative approach to addressing the challenges facing traditional agriculture, such as climate change, urbanization, and population growth. By enabling precise control over environmental factors, CEH enhances resource efficiency, allows year-round crop production, and reduces environmental impacts. This chapter discusses the critical role of CEH in creating sustainable and resilient agri-food systems. It explores key advancements in CEH technologies, including greenhouses, vertical farming, hydroponics, and aeroponics, along with successful case studies from various global regions. Despite high initial costs, CEH systems provide long-term economic benefits, foster local economic growth, and contribute to sustainability by minimizing water usage, carbon emissions, and pesticide dependency. However, challenges like energy consumption and waste management require continued innovation. This chapter provides insights into the current state of research in plant genetics and microbiome management and the future potential of integrating artificial intelligence and blockchain technology to improve CEH. Collaborative efforts are essential to advancing CEH and building a resilient, sustainable global food system.

Keywords: Agriculture, Controlled environment, Climate resilience, Crop production, Economic growth, Global market, Horticulture, Innovation, Policy, Productivity.

INTRODUCTION

The global agricultural sector is undergoing a significant transformation due to challenges like climate change, urbanization, and population growth, which threaten the sustainability of traditional agriculture [1]. Unpredictable weather patterns, extreme temperatures, droughts, and floods, all exacerbated by climate change, severely impact crop yields [2]. Urbanization further reduces arable land,

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increasing competition for resources like water and land [3]. Additionally, population growth drives food insecurity as current agricultural practices struggle to meet the rising demand [4]. To address these aforementioned challenges, there is a need for more sustainable agricultural practices. Controlled Environment Horticulture (CEH) presents a promising solution, allowing crop production in settings where environmental factors such as light, temperature, humidity, and CO₂ are precisely managed.

CEH involves techniques and technologies to optimize horticultural practices and yield within a controlled environment, offering a revolutionary approach to sustainable agriculture [5]. CEH enables year-round crop production, optimizing resource use efficiency, reducing dependency on seasonal and location-based factors, and minimizing the environmental impact of farming. This approach is gaining popularity due to its versatility, high product quality, elimination of pesticides, and potential to reduce transportation costs [6]. Controlled environment horticulture allows for the cultivation of a variety of plants, such as leafy greens, herbs, tomatoes, strawberries, and ornamental plants [7]. These crops thrive in controlled settings because they have shorter growth cycles and can be sold at a higher market value, making them perfect for this type of agriculture. This chapter provides a comprehensive analysis of the current state of CEH, exploring its technological, economic, and environmental aspects and offers insights into future trends and potential challenges.

TECHNOLOGY ADVANCEMENT OF CEH

Greenhouse Technology

Greenhouse technology is a key component of CEH, providing a controlled environment ideal for plant cultivation. Greenhouses, made from transparent materials like glass or polyethylene films, protect crops from adverse weather and pests, enabling year-round production [8]. Advanced greenhouses incorporate automated systems for irrigation, nutrient delivery, and pest management, which enhance resource efficiency and reduce labor costs [9]. Additionally, artificial lighting and HVAC systems help to maintain optimal growing conditions, supporting plant health and productivity even in closed environments like the greenhouse [10].

Vertical Farming

Vertical farming involves growing crops in vertically stacked layers, maximizing space use, particularly in urban areas. Vertical farms can produce crops year-round with reduced environmental impact by utilizing LED lighting and advanced

climate control systems [11]. This method conserves water and minimizes pesticide use, promoting a more sustainable form of agriculture [12].

Hydroponics and Aeroponics

Hydroponics is a soil-less cultivation method using a nutrient-rich water solution, offering precise control over nutrients and promoting higher yields. It is highly efficient in water use and eliminates the risk of soil-borne diseases, making it ideal for CEH setups [6].

Aeroponics, another CEH method, grows plants with roots suspended in the air, periodically misted with nutrients. This system enhances oxygenation, leading to faster growth and higher yields while using minimal water, making it suitable for resource-scarce areas [13].

CASE STUDIES OF SUCCESSFUL CEH IMPLEMENTATIONS

Gotham Greens, USA

It utilizes advanced greenhouse technology, such as full-spectrum LED lighting, automated climate control systems, and hydroponic growing techniques. These technologies allow for year-round production of leafy greens and herbs, achieving higher yields per square foot compared to traditional farming methods. The use of hydroponics significantly reduces water usage by up to 90% compared to soil-based agriculture, demonstrating the potential of CEH systems to enhance urban food security while minimizing environmental impact [14].

Sundrop Farms, Australia

It uses seawater desalination, solar power, and controlled environment greenhouses to grow tomatoes in a desert climate. The farm's climate control systems, including full-spectrum LEDs and CO₂ enrichment, optimize growing conditions and enable year-round production despite harsh external conditions. Sundrop Farms' integration of renewable energy and sustainable water management demonstrates the adaptability of CEH technologies in extreme climates, offering a viable solution for food production in water-scarce regions [15].

Sky Greens, Singapore

As the world's first commercial vertical farm, it employs a patented hydraulic-driven system to rotate stacked growing trays, ensuring each plant receives adequate sunlight. The farm integrates full-spectrum LED lighting and an efficient irrigation system that uses gravity to reduce energy consumption. By growing

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