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# Greenhouses

Cultivation Strategies for the Future

*Edited by Ahmed A. Abdelhafez*





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# Greenhouses - Cultivation Strategies for the Future

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# Agricultural Sciences

Volume 26

## Aims and Scope of the Series

The importance of agriculture cannot be overstated. It helps sustain life, as it gives us the food we need to survive and provides opportunities for economic well-being. Agriculture helps people prosper around the world and combines the creativity, imagination, and skill involved in planting crops and raising animals with modern production methods and new technologies. This series includes two main topics: Agronomy and Horticulture, and Animal Farming. This series will help readers better understand the intricacies of production agriculture and provide the new knowledge that is required to be successful. The success of a farmer in modern agriculture requires knowledge of events happening locally as well as globally that impact input decisions and ultimately determine net profit.



# Meet the Series Editor



W. James Grichar has been employed with Texas A&M AgriLife Research for over 45 years with an emphasis on research in agronomy, plant pathology, and weed science. He obtained his BS from Texas A&M in 1972 and his Masters of Plant Protection in 1975. He has published 195 journal articles, over 330 research reports and briefs, 11 book chapters, and over 300 abstracts of profession meetings. He also directs research in many crops including corn, grain sorghum, peanuts, and sesame. He has held various positions in different professional societies including the American Peanut Research and Education Society, Southern Weed Science Society, and Texas Plant Protection Conference in addition to being Associate Editor for Peanut Science and Weed Technology. Significant accomplishments have included spearheading efforts to determine the optimum planting time for soybean production along the upper Texas Gulf Coast. These efforts have shown growers that soybean yields can be improved by 10 to 20% by following a late March to early April plant date. He also has been instrumental in developing a herbicide program for peanut production in the south Texas growing region. Through the development and use of herbicides that are effective against major weed problems in the south Texas region, peanut yields have increased by 25 to 30%.



# Meet the Volume Editor



Professor Ahmed A. Abdelhafez is the Head of the Department of Soils and Water at New Valley University in Egypt. He earned his Doctorate in Environmental Science and Engineering from Tongji University in China and has expertise in soil remediation, bio-char technology, and climate-smart agriculture. His international experience includes roles in South Korea and China, and he serves on various editorial boards. Professor Abdelhafez has authored multiple books and over 100 peer-reviewed articles. He is a Fellow of the Academy of Scientific Research and Technology in Egypt and is registered as a consultant with the FAO, dedicated to promoting sustainable environmental solutions and agricultural development.



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# Preface

This book, titled *Greenhouses – Cultivation Strategies for the Future*, compiles an extensive array of chapters that delve into the forefront of contemporary greenhouse methodologies. It conveys a global perspective on the significance of greenhouses, extending beyond conventional horticulture to encompass emerging sectors such as aquaculture and vertical farming. The discussions presented, ranging from enhancing microclimates and humidity regulation to incorporating artificial intelligence and climate-resilient practices, underscore the revolutionary impact of innovation within the agricultural domain.

We have compiled insights from researchers, practitioners, and thought leaders who are currently shaping the future of food systems. Their contributions provide both theoretical foundations and practical applications, rendering this book a significant resource for scientists, agronomists, policymakers, educators, and all individuals interested in advancing sustainable agriculture.

Our objective extends beyond merely documenting the current state of greenhouse technologies; we also aim to inspire action and creativity for future systems. Whether you are a researcher in horticultural science, an entrepreneur in the agri-tech sector, or a policymaker investigating resilient food strategies, we aspire for this book to serve as a guiding framework for more intelligent, inclusive, and impactful cultivation systems.

Let us reconceptualize the greenhouse not merely as a framework of glass or plastic but as an emblem of innovation, resilience, and sustainable development.

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Section 1

A Clear Vision for the Future  
of Greenhouse Farming

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## Chapter 1

# Exploring Future Cultivation Strategies in Greenhouses

*Ahmed A. Abdelhafez, Sami A. Al Dhumri,  
Mohammed S. Shaban, Omar K.M. Elgeheny,  
Asmaa S.H. Saleh and Aya Sh. Metwally*

### Abstract

The greenhouse not only shielding plants but also allowing for the use of techniques that cannot be used in the fields will also increase certainty and enable businesses to better respond to demand patterns. This chapter looks at advancements in greenhouse cultivation strategies, including improved climate management, integrated pest management technologies, and other resource efficiency technologies. It examines how greenhouse farming helps in the sustainable production of food and medicinal plants, giving special importance to precision agriculture, artificial intelligence, and machine learning technologies as enablers of improvements in yield and quality. Additionally, the chapter cites novel approaches in the realm of sustainable agriculture as vertical farms, which represent disruptives strategies for the future of greenhouse systems and the integration of renewable energy sources. Additionally noted are the major challenges that the sector will have to also grapple with including climate variability, high operational costs, and the urgent need to automate processes to boost efficiency. By harnessing cutting-edge technologies and eco-friendly approaches, greenhouse farming can dramatically aid in meeting the worldwide goals of food security and sustainability.

**Keywords:** greenhouse cultivation, sustainable agriculture, vertical farming, resource efficiency, automation, renewable energy, smart agriculture, food security

### 1. Introduction

One of the most significant agricultural and environmental practices currently is the cultivation of vegetables, flowers, and plants within the controlled environmental conditions. In recent years, particularly following the advent of modern plastic or film-covered greenhouses, this cultivation approach has revealed distinct characteristics and advantages in fostering stable crop production. Greenhouse cultivation is essential to global food security as it provides sustainable and dependable crop yields while alleviating environmental pressures such as extreme weather, pests, and

diseases [1]. Technological advancements, particularly those driven by artificial intelligence (AI), are transforming greenhouse agriculture by optimizing climate control, irrigation, and pest management through predictive analytics and automation [2]. The incorporation of AI in greenhouse farming has been demonstrated to enhance efficiency, minimize resource consumption, and improve sustainability metrics, thereby aligning with global initiatives aimed at promoting energy-efficient and environmentally responsible agricultural practices [3]. As the demand for sustainable food production continues to grow, greenhouse agronomy must evolve to integrate emerging technologies that boost productivity while decreasing ecological impacts [4].

### **1.1 Significance of greenhouse cultivation**

The greenhouse industry must take advantage of its considerable potential to contribute to meeting the ever-increasing global demand for environmentally and hygienically safe food [5]. There are many reasons why greenhouses can be good options for future food production. Greenhouse operators can minimize climate-related risks by creating an ideal microclimate for plants using many customizable features, such as natural ventilation, screens for energy efficiency, artificial lighting, and carbon dioxide dosing, among others [6]. They can decouple production from external conditions, essentially allowing for the possibility of a given crop being produced consistently over the year with a controlled quality of the end product. The excellent physical protection from the environmental stressors and pathogens achievable in greenhouse environments is particularly interesting for integrated pest management and plant disease control [5, 7]. The costs of implementing IPM-based solutions in intensive greenhouse farming may be high, but over the long term they are generally considered to be more economically favorable in a smart greenhouse context [8].

We must start to change our traditional agricultural perspectives and develop not merely adaptations of today's best greenhouse technologies, but innovative new ones that make the best possible use of the unique positive facets of a greenhouse cultivation system to meet the needs of the future [9]. The effects of climate change that are ever more noticeable may already be impacting agriculture, influencing plant phenology and the spread of pests and diseases [10]. Water is a scarce resource and we must not waste it; the same applies to carbon, and our greenhouse crops must be even better suited to capture and fix carbon into plant mass. Agricultural practices that are efficient in resource consumption are low in energy consumption, particularly in irrigation, and they prevent pollution [11]. Any soil loss must be prevented, and all sources of pollution must be combated. The specific challenges faced in meeting these requirements in a greenhouse system must be carefully addressed [12].

### **1.2 The role of greenhouse cultivation in medicinal plant production**

In the production of medicinal plants, the use of greenhouse cultivation stands as one of the most significant inputs because it helps create an environment that helps to maximize the potential of growth irrespective of the conditions outside. Temperature, humidity, light exposure, and soil content can be easily controlled in green house thus allowing for year round production and favorable climatic conditions for growth. This controlled environment is useful in the case of the medicinal plants, as these require particular environmental conditions for biosynthesis of effective compounds. First, greenhouses protect plants from pests, diseases, and unfavorable weather conditions whereby enhancing the health of the plants and the concentration of therapeutic

compounds in the medicinal products [3]. However, greenhouse cultivation enhances the proper management of resources such as water and use of fertilizer hence making greenhouse cultivation of medicinal plants more effective for large-scale production. This way, a farmer can use much lesser water as well ensure that the plant takes in all the nutrients required to produce maximum yields thus reducing the effects on the environment [13]. Moreover, the conditions created by greenhouses also allow the farmers to utilize the best methods in fertilizing the plants; this way the amount of nutrition given to the plants is received in the most optimal manner and this leads to the plants being more healthy and vigorous. Additionally, greenhouses confine damages from hard weather conditions including rain, hail storms, high winds, and temperatures. Through excluding these bad weather factors, greenhouses help slow down cases of destruction, breakage, and loss, hence providing constant and stable quality supply of medicinal plants throughout the year [14]. This stability in supply is important in adequately responding to this ever growing demand for herbal remedies so that patients and consumers can have access to the necessary medicinal products regardless of the season. Other than creating a stable environment, green houses also help in the putting in place of the pest control measures [15]. Through minimizing on pest incidence, farmers are saved from using many chemicals which in turn means that the concentrations of such chemicals in medicinal plants are also reduced, hence enhancing the concept of organic agriculture. This not only increases the protective and qualitative characteristics of medicinal products, but also has a positive effect on the sustainability of cultivation.

In addition, due to the fact that the plants are grown in greenhouses, the changes in various plant growth factors can be easily monitored and controlled [16]. Depending on the period of time that light exposure is carefully regulated for the plants, growers can achieve enhanced rates of photosynthesis and active pharmaceutical compounds for medicinal plants. Seasonal changes in the humidity levels can be regulated to avoid either suffocating plants with excessive moisture or depriving them of moisture which would be fatal to their health or lead to the development of certain diseases such as fungal [17]. On balance, this study has found that the greenhouse cultivation of medicinal plants offers a sustainable and efficient technique of growing high quality crops. This is because through greenhouses there is controlled conditions for growth, conservation of limited resources, protection against harsh weather, and overall control of pests. This approach caters for the increasing market trend in the use of natural products more especially herbal products while ensuring quality and stock is constant throughout the different seasons. As the usage of the medicinal plants increases, the idea of greenhouse cultivation is the best approach given the needs of the patients and the customers.

## **2. Current challenges in greenhouse cultivation**

Various challenges plague greenhouse farming. First and foremost, regulating the greenhouse can prove to be complex. Two primary components of this are heating and cooling, including temperature set points, air circulation, the efficiency of the heating system, and whether there exist heating pipes embedded in the ground [18]. Humidity can also be a challenge, problematic in more ways than just animal guard control. Air circulation can help prevent disease outbreaks in the first place, as well as being critical in keeping temperature and humidity levels equal throughout the greenhouse. Balancing time and natural resources between crops is yet another

factor to be considered [19]. Cultivating high-quality, healthy crops while managing a variety of pests and diseases can be time-consuming. Farms with large acreage face an uphill battle in this respect. The installation of relatively new technologies such as fans, climate control systems with the capacity to monitor greenhouse conditions from a remote location, and hydronic heating systems require a relatively high initial investment [20]. These systems are greenhouse fans that are installed extra-high in the greenhouse, designed to work in conjunction with typical ventilation systems. These types of solutions are not entirely hands-off though, as skilled help is required to operate the systems [21]. Cultivation of ornamentals also faces the insurmountable challenge of local laborers both being averse to greenhouse work and not being abundant. As the workforce becomes smaller and smaller, new technological innovations or even changes to greenhouse design will be required before complete automation is possible [22]. In addition, new cultivation technologies sometimes need to be streamlined or consolidated in such a way that it is possible for growers with less familiarity on development sites as well as smaller profits to capitalize on them [9].

## 2.1 Climate control

Climate control is a critical factor in greenhouse cultivation, as temperature, humidity, and light intensity directly influence plant photosynthesis, transpiration, evaporation, and overall greenhouse climate, ultimately affecting crop growth and yield. While optimizing climate conditions has long been a focus in horticulture, achieving an ideal balance remains a challenge. Effective climate management necessitates precise control over temperature, humidity, carbon dioxide levels, and light intensity within the greenhouse to promote optimal plant growth [23, 24]. Solar radiation serves as a primary energy source for greenhouse environments, playing a dual role in both supporting plant photosynthesis and contributing to excess heat accumulation. On cloudy days, artificial lighting systems compensate for the reduced natural radiation, ensuring consistent light conditions. However, excessive solar radiation can lead to overheating and increased water loss through transpiration, which can negatively impact plant health and energy efficiency. To counteract these effects, greenhouse climate control systems must incorporate effective strategies to regulate solar radiation exposure. Several mechanisms are employed to mitigate the impact of solar radiation on indoor greenhouse environments. These include the use of automated shading systems, reflective or absorptive materials on greenhouse structures, evaporative cooling methods, and optimized ventilation strategies. Solar shading curtains, for instance, dynamically adjust light penetration and thermal load within the greenhouse, reducing temperature fluctuations caused by varying solar intensity [25]. Additionally, advanced climate control systems integrate real-time environmental sensing and automated responses to external weather conditions, ensuring a stable and energy-efficient indoor climate. The challenge lies in designing direct and adaptive systems that maintain optimal greenhouse conditions despite the unpredictable influence of external factors such as wind, solar intensity fluctuations, and cloud cover. Achieving an effective trade-off between maintaining ideal climatic conditions and minimizing energy consumption is crucial. Prioritizing specific environmental parameters often requires strategic compromises, such as regulating temperature at the expense of higher humidity levels or *vice versa* [26]. Since the optimal temperature range within a greenhouse depends on multiple variables—including crop type, regional climate conditions, and technological innovations in horticulture—continuous advancements in greenhouse research are necessary. Traditional climate control

systems tend to prioritize crop yield and quality by optimizing growing conditions, often without considering the energy demands of the greenhouse's embedded systems. However, efficient management of climate control and energy-consuming appliances can significantly influence overall energy consumption and operational costs in horticultural production [3, 27].

To further enhance climate control strategies, modern sensing and actuating technologies are extensively employed in agricultural applications. These technologies monitor both outdoor weather patterns and indoor environmental conditions in real time. By automating heating, cooling, lighting, and irrigation systems based on micro-meteorological changes—such as fluctuations in air temperature, global radiation levels, or shading effects—greenhouse operations can achieve higher energy efficiency while maintaining optimal growth conditions for crops [28].

### 3. Emerging technologies in greenhouse cultivation

Modern greenhouses are being shaped by various technological advancements that target high-quality crop production with minimal environmental impact. For economic and environmental sustainability, the adoption of advanced systems is necessary to cope with a growing world population and decreasing availability of production resources such as labor, water, and fertilizers (**Table 1**) [29]. The automation

Technology	Description	Benefits
Automation systems	Facilitates the automation of climate control, irrigation, and resource management to enhance operational efficiency and minimize the requirement for manual labor.	Lowers labor expenses, increases operational efficiency, and improves the consistency of crop growth.
Data analytics & AI	Evaluates extensive datasets to refine decision-making processes, maximize agricultural productivity, and improve the distribution of resources.	Facilitates predictive modeling, minimizes waste, and enhances profitability.
Sensors & IoT	Observes environmental variables including temperature, humidity, and soil conditions in real time.	Enhances precision in climate control systems, and significantly reduces water usage and energy consumption for better efficiency.
Wireless communication networks	Facilitates effortless connectivity and data exchange among greenhouse components, thereby enhancing overall integration.	Guarantees real-time responsiveness, significantly enhances overall system reliability, and improves automation processes for greater efficiency.
Precision agriculture	Employs real-time surveillance to modify water, nutrient levels, and environmental parameters in accordance with the requirements of the crops.	Enhances the efficient use of available resources, boosts overall crop yield, and significantly reduces the negative environmental impact.
Autonomous systems	Utilizes automation, artificial intelligence, and robotics to create self-regulating greenhouse operations that require minimal human involvement.	Facilitates entirely automated greenhouse functions, diminishing reliance on human labor while enhancing scalability.

**Table 1.**  
*Key technologies employed in modern greenhouses.*

of greenhouses is believed to be an essential component of operational scheduling and control to optimize resources and the utilization of the workforce while assuring high-quality produce, energy savings, and environmental impact reduction [23]. The adoption of these systems makes it possible to manage operations, crops, and resources in a precise and intelligent manner. In this new scenario, novel and cutting-edge technologies have gained visibility within horticulture: automation, data analytics, and sensors are providing increasing value to a range of greenhouse facilities. Improvements in computing, wireless communication networks, and data storage have led to the possibility of integrating advanced sensor systems to deliver precise information rapidly [4]. Through data assimilation, hypotheses can be strengthened, refuted, or derived. Furthermore, extrapolations between sensors and exploration of data across various scales are possible to optimize the operation of greenhouses. The availability of these systems may allow for a significant reduction in resource consumption and waste while enhancing the operational efficiency of a facility [30]. The main purpose and benefit of employing such methodologies in the greenhouse is the delivery of precision agriculture. This requires monitoring the containment system, soil condition, fertilizer distribution, and weather systems to be operable in real time in order to act on any variation in crop growth requirements [31]. The potential challenges to the adoption of these technologies are discussed, as well as the potential of integrating all components to lead to a fully autonomous operation.

### **3.1 Artificial intelligence and machine learning**

Artificial intelligence (AI) and machine learning techniques provide new and sophisticated tools for data and information management. The main scope of these technologies is to help and support growers in decision-making, increasing the effectiveness of individual decisions based on real, on-site data and forward-thinking planning [2, 23]. According to this, the AI potential fields of application are to make predictive analytics reliable and reusable, based on meaningful data [32]. In the horticultural field, a great number of possible applications could be considered, and grower support seems to play a crucial role, principally in the field of plant protection, being able to support predictive diagnostic methodologies [33].

Prognostic and diagnostic predictions for enhancing plant protection mechanisms are already being implemented, predicting potential pest attacks. Beyond these applications, in daily cultivation activity, AI could help to monitor the crop, assisting with crop forecasting and the decision support systems for optimal resource allocation [34, 35]. A diverse array of ML models is utilized, categorized into supervised, unsupervised, semi-supervised, and reinforcement learning methodologies. Supervised learning algorithms, including support vector machines (SVM) and neural networks (such as multi-layer perceptrons and convolutional neural networks), are prevalently employed for tasks such as disease detection, crop growth forecasting, and climate modeling, thereby augmenting the accuracy of greenhouse monitoring [2, 33]. In addition, unsupervised learning techniques, such as K-means clustering for the categorization of plant species and principal component analysis (PCA) for the reduction of dimensionality, aid in the identification of patterns within greenhouse datasets [36]. Semi-supervised learning tools like hidden Markov models (HMMs) facilitate predictive analyses pertaining to various stages of crop growth, while reinforcement learning approaches, exemplified by Deep Q-Networks, permit dynamic modifications in climate control strategies, thereby optimizing the energy efficiency of greenhouse operations. Supported by AI, crop monitoring practices might be

further extended, guaranteeing crop quality. AI, when combined with machine learning models, could support autonomous cultivation of the greenhouse, modeling the behavior of autonomous processes in response to adaptive cultivation strategies.

Indeed, machine learning (ML) stands out as one of the key AI tools and is mostly used, as verified by the number of papers and publications submitted and accepted on AI applied in greenhouse cultivation. Based on the way in which the models are built, several methods can be classified as supervised, unsupervised, or semi-supervised machine learning. Such a division allows growing AI in greenhouses from plant recognition and identification to algorithms able to learn and adapt to new data [2, 36]. A further evolution of the tools will be achieved by reinforcement learning, allowing AI algorithms to behave like humans. In this perspective, AI using machine learning in greenhouses will be able to satisfy consumer demand in terms of fruit. From a commercial perspective, a berry marketing company needs the average estimated berry yield of the season in order to make deals, knowing their quantities according to classes [37]. The advantage of the system in terms of increasing the average yield and reducing environmental footprints is approximately 10%. At the same time, the development and possible evolution towards machine learning of AI tools in a complex and uncertain environment like the greenhouse environment are strictly linked to the management aspects based on environmentally conscious criteria [38]. New AI techniques might represent a new advancement in the management of climate control strategies. There are several aspects to consider before a successful implementation of AI in greenhouses, mainly focusing on financial and technical aspects, and on personal expertise requests. The AI empowerment and its usage and application implementation will lay the foundation for an overall consideration in which the old and tested system should be merged with the new generation AI technologies [39].

#### **4. Sustainable practices in greenhouse cultivation**

As the importance of “green” practices within greenhouse cultivation increases, many new strategies are introduced to reduce waste and resource consumption [40]. Organic practices seek to utilize the chemicals within compost and animals to produce needed resources, such as fertilizer or soil amendments [41]. Biodiversity in greenhouses aids in enhancing soil health through aeration and decomposition of organic matter such as wood chips, leaves, and other waste [42]. Both of these practices center on avoiding the use of chemicals or energy where other less costly means of mitigation exist. Organic farming methods can also be more beneficial for food safety. Water recycling within a greenhouse has the potential to drastically reduce the amount of water, be it tap water or rainwater, necessary for a successful crop, creating savings for a business through conservation [43].

Water conservation has difficult requirements and processes to undergo to offer the potential savings a business would need to justify the costs. Other ways to save water in a greenhouse include installing gutters along the edges of the greenhouses to collect rainwater for using later. Additionally, the use of drip irrigation has been considered for many systems. This system can offer a number of benefits for water conservation and soil moisture monitoring techniques [44]. One of the most substantial benefits of drip tape is its ability to deliver water to the roots of the plant, as well as allowing soil to dry between watering cycles to ensure excess water does not damage root systems of plants. Additionally, because of the lack of evaporation, the irrigation remains leading to minimal to no water loss. Up to 95% of water is extracted from

the soil and utilized by the plant when using drip irrigation methods. Greenhouses nowadays are not only focused on production but also on the environment [45]. Some greenhouses are being built with clearer plastic to allow for natural light to be harvested. It is necessary, though, for the use of the right techniques and double-testing methods to work directly with the provision of integrated pest management. By decreasing energy consumption and using renewable and natural resources, anyone can create a conscious decision to help the environment [3, 46].

#### **4.1 Water and energy conservation**

Adoption of water and energy-saving strategies by agribusinesses can have a significant impact on the ability of greenhouses to produce in an efficient manner and create an even more marketable “green” food choice for consumers [3]. Several management approaches are available to conserve both of these resources, and most have been determined to be highly effective in experimental and real-world conditions [47]. Although numerous conservation strategies are available, they will be treated separately within this analysis. However, the close connections between water availability or usable growing medium volume, plant performance, and atmospheric water vapor levels indicate that the integrated use of these management approaches is valuable [48].

The current greenhouse industry trend has been limited to the investigation of the utilization of renewable energies to offset the costs to the production system of purchased electrical energies, specifically for the production of electricity with photovoltaic panels. Less common are greenhouse panels and systems that supplement energy needs with integration systems of micro-wind or water power systems. Geothermal heating may further minimize the potential for global climate alteration. A system’s convenience from external renewable energy supply allows maximization of crop yields using production space that would otherwise be used to accommodate non-renewable energy resources [49, 50]. This idea was historically exemplified in the use of a subterranean greenhouse by Europeans and transplanting the concept to a location with synergy between primary energy resource and energy use most immediately focuses on the use of geothermal, and thus underground greenhouse design. Retrofit of an existing system comes with difficulties, as markets for incorporation are not prepared for optimized integration. The process of selling renewable excess energy *via* subsidies is further encouraged by the use of cutting-edge, non-integrated PV [51, 52].

Several general management practices are available to conserve both of these resources and have been found to be effective in general. However, one of the most common restraints of applicability is cost, because each of these practices requires capital inputs in addition to the energy water use, and added equipment should a facility wish to invest in all four practices; the costs can become local, sometimes prohibitively expensive [53]. Required training is also an issue, because when such technology is not widely used, many workers must be instructed in how to operate new systems. This includes a backward teaching framework that must be utilized when an older or more traditional worker group is being trained in the use of new machinery [54].

### **5. Future trends and innovations**

The future of greenhouse cultivation is currently being framed in the context of new developments in technological advancement and sustainability. These combined

shifts are generating significant changes in how we produce our food. Feeding both the new technologies creating it and the dramatically changing demands that will characterize food markets in the coming years, future cultivation strategies continue to shape people's ideas in policy, practice, and consumer sentiment and demand [55]. At one level, greenhouses are becoming smarter and revolutionizing farming in terms of diagnostics and treatment strategies, and tech companies are mixing and migrating into different areas of hardware and software for the greenhouse of the future. At another level, the ability to manipulate and genetically modify plants at the cellular level will always alter the types of crop products produced in greenhouses, enhancing those now grown out of season as elite products [56, 57]. In a different domain, for agronomists and growers, the demand for more precise environmental information and extremely controlled, space-specific conditions is changing the face of greenhouse units, and the data that these tools create may aid a production focused not just on increasing yields but on crucial ideas regarding waste versus profit. Moreover, decision-making in the near future will be based on the value of harnessing increasingly rich and complex fields of data toward those ends [3]. Optimal growing conditions will be created for particular purposes and for particular groups of cultivars within cultivation units that are standalone but networked in terms of central command and control. Most changes and innovations in future agriculture tend toward the progressive amalgamation of data, power, and control [58]. Researchers warn how much of the Utopian visionary system of precision agriculture is still on the way and not yet arrived. However, this does not limit others from continuing to try. It is argued that precision agriculture is, as a matter of fact, a selectively reshaped co-production of agriculture and high-tech science that will finally see its development as a result of a multidisciplinary filter process, even at the levels of innovation and value-added chains. Thus, the multiple interdependencies harbored within the production process and within the rapidly evolving economic biosphere of new foods will require openness to adjacent fields and focused investment, particularly in research and development agendas transitioning toward high-tech and large-scale innovations [59, 60]. Variably known as city farms, they are considered the next leap in biotechnology's rapidly advancing sphere to expand food supplies to states experiencing severe resource deprivation while meeting ecological care regulations [61].

## **5.1 Vertical farming**

Vertical farming is a transformative farming practice where food is produced in vertically stacked layers. It often incorporates controlled-environment agriculture, which aims to optimize plant growth and resource consumption [62]. There are different configurations of vertical farming: Some variations use soil, hydroponic, or aeroponic growing methods, while others could employ drip, ebb, and flow, or nutrient film techniques. These types of systems can operate within high-rise buildings, vacant underground subway and train stations, and disused parking lots. This innovation can have multiple benefits [63]. Vertical farming occupies a much smaller amount of land by increasing the number of layers, or 'stories,' where crops are grown. Vertical farms use less water; hydroponic and aeroponic systems use a fraction of the water needed for field-based agriculture. Additionally, without pesticides, the outputs from aquaponic and hydroponic systems can be considered beyond conventional organic [64, 65].

This is important for urban agriculture, where local cities can have primary access to food, reducing the carbon footprint of farming practices and stimulating local

urban economies. Being not reliant on field-based agriculture, vertical farms could grow year-round regardless of the outdoor climate [61, 66]. While a vertical system is technologically impressive, initial investments are significant. Aquaponic, hydroponic, and aeroponic systems all use electric pumps, which require large amounts of power, estimated at 10% of the farm's energy expenses. Moreover, the use of organic plant feed, toxins for purifying fish waste, optical wavelengths for plant growth, and battery-like backup power systems makes the technology significantly more complex. Despite this, integrating vertical farming methods with traditional methods in a greenhouse could minimize this complexity and promote innovative practice within urban agriculture [61, 67].

## **6. Conclusions**

Greenhouse cultivation is anticipated to serve a pivotal role in the future landscape of agriculture by incorporating technological advancements, sustainable methodologies, and data-driven approaches to improve productivity and resource efficiency. This chapter has examined several innovations, such as precision climate management, artificial intelligence, and vertical farming, all of which enhance crop yields, promote resource conservation, and foster environmental sustainability. In spite of the challenges associated with climate variability, substantial operational costs, and the necessity for automation, greenhouse farming stands as a feasible solution to tackle global food security issues. By harnessing renewable energy sources, maximizing water and energy utilization, and embracing state-of-the-art automation technologies, greenhouse agriculture can markedly diminish its environmental impact while ensuring consistent year-round production of high-caliber crops. Looking ahead, interdisciplinary collaboration, investment in research, and policy advocacy will be essential in propelling the advancement of greenhouse farming, establishing it as a fundamental element of sustainable food production on a global scale.

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## Chapter 2

# Perspective Chapter: Vertical Farming Innovations – A Brief Overview

*Bekhruz I. Abdurakhmonov*

### Abstract

Vertical farming, a widely implemented innovation in modern agriculture, offers a promising path toward sustainability. It allows for the production of agricultural products in limited non-soil and water-scarce conditions, thereby reducing negative ecological impact. For example, InFarm (Germany), founded in 2013, has saved 205,000 sqm of land and uses 95% less water than traditional farming. These farms can also reach higher productivity by yielding 20 times more per acre in comparison with traditional farms due to the effective use of farm space; for instance, a 1000 sqm farm using iFarm Leafy Greens technology can produce 3400 kg of food monthly, generating 57,800 \$ in revenue. In this brief overview, I explore the potential of vertical farming to not just describe its revolutionizing impact on agriculture but also its significant role in hunger reduction, boosting the economy, and strengthening food security programs. However, challenges like high energy costs and initial investment needs remain. While there is a need for further technological advancements, including the application of new biotechnologies, robotics, and AI, vertical farming is poised to become a key solution for food production in the face of global climate change and human population increase.

**Keywords:** vertical farming, smart agriculture, crop productivity, economic value, artificial intelligence, robotics

### 1. Introduction

Throughout the history of human farming, it has been one of the most crucial points that has sustained and is still sustaining people with vital energy. However, the environment, soil, population, and other farming factors have changed. Growing plants without chemical fertilizers and getting sufficient food supply is becoming more complicated. At the same time, these fertilizers negatively impact soil and, eventually, the drinking water as the herbicides and pesticides applied to the plants wash out into our rivers and oceans [1]. These challenges of traditional farming and its environmental impact underscore the urgent need for alternative solutions, such as vertical farms [1], making this topic highly relevant and essential.

First, the concept of vertical farms was opened and described by professor of environmental health sciences and microbiology Dickson Despommier in 2010. Generally, the idea behind vertical farms is that these farms would grow food in properly designed buildings in cities without the need for soil, which will, in the long run, lead to cities without waste, water reusing, and recycling facilities, decreasing pollution, and lots of other positive outcomes that will be discussed further on this report. One of the most inspiring examples of vertical farms today is InFarm (Germany), founded in 2013 by Osnat Michaeli and the brothers Erez and Guy Galonska. This farm has already saved more than 205,000 sqm of land and uses 95% less water for growing crops. Moreover, growing food year-round guarantees that its produce is free from chemical pesticides, herbicides, or fungicides, demonstrating the potential of vertical farming and inspiring confidence in its viability [2].

Despite the recent positive changes, such as large extensions in the vertical farming industry worldwide, challenges still need to be solved. Production costs remain somewhat expensive, and as it is a relatively young market, there needs to be more knowledge in critical operational cases like environmental and engineering threats to long-term sustainability and profitability. Moreover, economic changes in supermarkets force vertical farms to scale fast and, at the same time, require products with quality, size, and nutritional value. As an evolving industry, vertical farming should adopt innovations in automation, lighting, engineering, and cultivation methods to stay in the market [3].

This chapter will analyze the viewpoints of vertical farms and innovations, followed by an analysis of traditional farming and its effects on the environment and economy. It will also consider the constraints of vertical farms and potential future technological solutions.

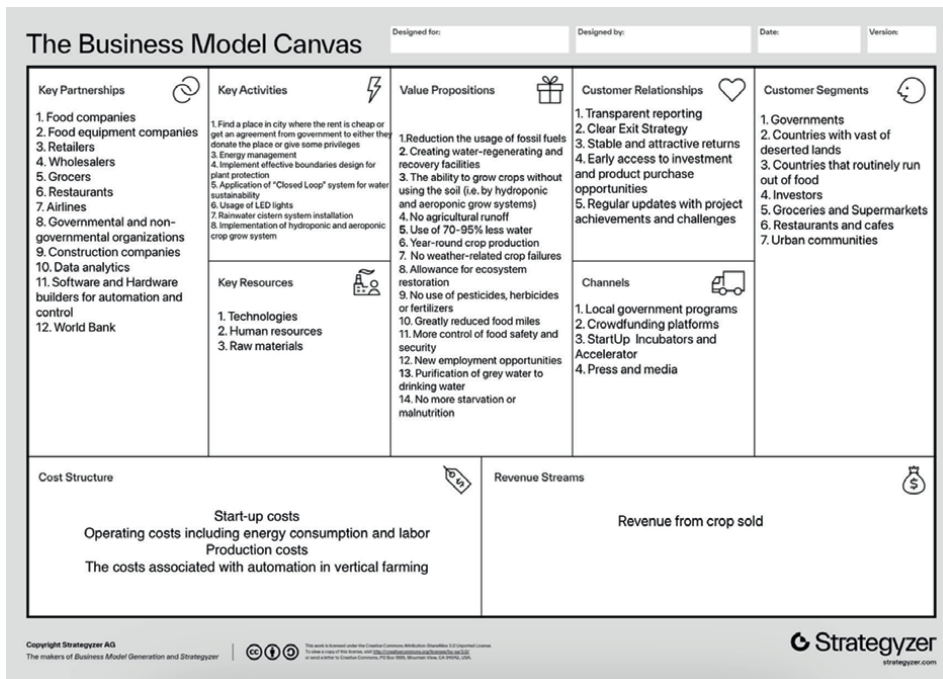


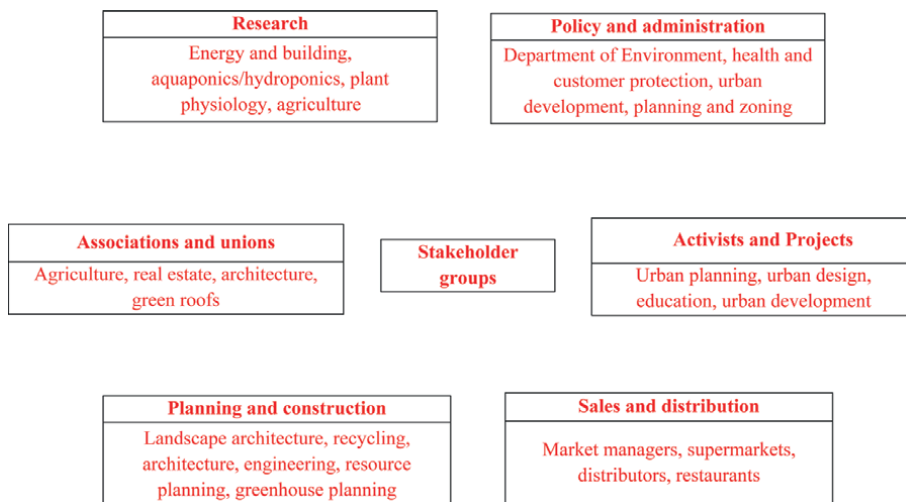
Figure 1. Business model canvas for vertical farm.

The success behind the Vertical Farms can be further clarified by creating an Osterwalder/Pigneur Business canvas to showcase the value of all Vertical Farms ([1]; **Figure 1**).

## 2. Customer segment

Vertical Farms have a diversified customer segment. Indeed, all countries could benefit from the environmental side of this concept, and to be more precise, it could potentially stabilize conditions of Middle Eastern states that now battle over limited water supplies and have unvarying diets due to the limited farmland and a harsh desert climate [1]. Moreover, countries that routinely run out of food would get a positive impact, meaning no more starvation or malnutrition, through the implementation of this industry. Regarding the economic aspect, the customer segment is diverse (see the chart below), starting with some private companies and investors potentially looking to make money in the long term and ending with restaurants and cafes, groceries, and supermarkets that can be supplied with food. Urban communities are another group that will gain an advantage from vertical farms, making the built environment greener and safer and creating more job opportunities (**Figure 2**).

InFarm, a German-based company, has transformed urban agriculture while conserving 205,000 square meters of land and 95% less water use than traditional farming by putting modular farming units in supermarkets and restaurants. AeroFarms (USA) is one of the world’s largest vertical farms, located in Newark, New Jersey. It produces more than two million pounds of leafy greens annually for substantial retail chains like Whole Foods and has contracts with local schools for fresh produce [4]. Sky Greens (Singapore) plants vegetables through an exclusive low-energy, water-driven approach, allowing them to sell locally in their immediate neighborhood with much less water and soil used [5]. These examples indicate that vertical farming can be practiced anywhere around the world, and it can serve various population groups.



**Figure 2.**  
 Various stakeholder groups.

### **3. Value proposition**

The position of oil is being taken by water. In other words, there is an ultimate scarcity of fresh water, as 70% of it is used in agriculture to grow crops [1]. However, throughout history, the human species has evolved to cope with the changing environment by discovering technological solutions that improve our quality of existence. The Vertical Farm concept includes various ways to address the water shortage problem. First, vertical farms use technology at their maximum capacity, and hydroponic and aeroponic growing systems replace soil-based crop growth. There is some 70% less water usage in hydroponics compared to traditional irrigation circuits in outdoor agriculture.

Similarly, the aeroponic system uses 70% less water than hydroponics. Hydroponics systems remove the need for soil by growing plants in a nutrient-rich water solution, giving fine control over the nutrient supply [6]. This lowers pesticide use and herbicide reliance while doing well in terms of increased growth rates and yields. Aeroponics goes one step further than this by suspending plants in the air and spraying their roots with a nutritious solution to maximize oxygen exposure and nutrient absorption [7]. For these reasons, both systems recycle nutrients and water to minimize waste and ensure efficient use of resources. Consequently, technical advances such as these demonstrate that vertical farms can produce up to 20 times more output per acre than traditional methods while showing their practicality and scalability [8]. They are effective in water conservation while reducing chemical pesticides and herbicides, improving food production systems' sustainability. Also, it helps decrease emissions by 67–92% compared to conventional greenhouses because food can be produced vertically, thus significantly reducing the need for transportation [9]. For instance, such systems' adoption by firms like InFarm has already saved almost 1.6 million food miles, translating to significant CO<sub>2</sub> [10].

Moreover, the gray and black water released from the building can be reused and recycled using technologies such as Cycle-Let. This technology initially collects wastewater in a buried pre-treatment trash tank that removes grit and gross solids. The effluent is then pumped into the biological treatment system, incorporating aerobic and anaerobic processes. Aerobic treatment oxidizes organic solids and converts organic nitrogen to nitrates; the anaerobic converts nitrates to nitrogen gas. Self-cleaning, tubular ultrafiltration membranes remove suspended solids and microorganisms; solids are returned to the biological treatment tank for further digestion. The effluent then passes through activated carbon absorbers, removing any remaining color and odor. Finally, UV (ultraviolet) disinfection and ozonation destroy any remaining microorganisms [11]. The reclaimed wastewater is stored in a reservoir until it is needed for hydroponics or aeroponics use [12]. The most beneficial part of using this technology is that it is fully automated and can be monitored and controlled remotely by computer or telephone connections, which leads to cost reduction in the personnel section. When it comes to the rain harvesting system, the rain is collected from the rooftop of a building and directed into storage called cisterns. Although rainwater may be used directly to grow plants, since it is often clean and chemical-free, it can be further filtered to make it suitable for drinking [13].

Conventional agriculture products travel 2000 miles on average, as farmers occupy lands with the best natural conditions for crop growth. Vertical Farms, conversely, can be settled wherever it is convenient, especially near the customers and without any ties to climate conditions. If incentives were created to establish vertical farms inside the city, food miles and greenhouse gas emissions would be significantly reduced.

Moreover, there is a high chance that these products will be freshly picked, never frozen, or even refrigerated. No storage would ultimately lead to reduced refrigeration and more savings of fossil fuels. Eventually, these farms will create a local, sustainable source of produce that will undoubtedly find its way into restaurants, cafes, and green markets. Generally, the amount of travel between the products of these farms and one's home will be measured in blocks, not miles, resulting in a massive cut in carbon emissions [1]. So far, Infarm has saved nearly 1.6 million food miles (about 3 million km) with its production methods. However, some argue that transporting small amounts of carbon-heavy goods over short distances may not always be as sustainable as importing significant quantities of food simultaneously. Despite this drawback, studies show that, as compared to greenhouses, vertical farms emit 67–92% less CO<sub>2</sub> overall [14].

Flooding has become a persistent issue in large parts of Southeast Asia and the Indian subcontinents. Recently, droughts have also taken their toll on agricultural output, particularly in Australia, the American Southeast, and sub-Saharan Africa. Farming only succeeds with water for irrigation. Loss of topsoil is another consequence of floods and droughts, the world's second most dangerous agricultural issue after the toxic effects of runoff [1]. These trends eventually lead to agricultural runoff. Even if flooding is not considered, most irrigation techniques result in substantial runoff from crops. Since every plant species needs more water than it receives from rain events, runoff is unavoidable to maximize yields in typical outdoor agricultural cultivation.

Most advanced farming operations nowadays produce runoff heavy with silt, fertilizer, herbicides, and pesticides that typically ends up in a river on its route to the estuary. The main reason for the usage of these chemicals by traditional farmers is to counteract unwanted diners, such as insects and microbial pathogens, that may thrive in outdoor settings, surpassing their nutritional needs and causing disaster in the global agricultural environment [1]. Given these circumstances, vertical farming has shown to be a viable option to address these multi-faced challenges and improve the production of high-quality agricultural yields [15]. This new paradigm for agriculture represents a revolutionizing way of growing fresh, nutrient-dense foods in urban environments.

Through multitier cultivation, year-round production, and quicker development, vertical farming may increase yields while boosting productivity. Despite the current financial constraints, vertical farming is set to become more widely used as a preemptive response against food scarcity. In addition, cities are becoming megacities due to population growth and space limitations. In response to this trend, designers everywhere are pushing to adopt indoor farming methods to fulfill the potential of metropolitan areas to produce substantial quantities of food [16]. This method requires less land than traditional farming, promoting self-sufficiency in food production in cities while alleviating the strain on land and natural resources [17]. By addressing present agricultural issues, incorporating vertical farming allows possible ecosystem restoration while offering a sustainable response to the changing needs of expanding urban populations.

Regarding employment opportunities, a significant amount of skilled labor is needed to run these farms. There will be lots of spaces for managers, developers, architects, engineers, planners, data analysts, agronomists, waste-to-energy personnel, sales personnel, educators, security personnel, laboratory personnel (microbiologists, molecular biologists, technicians, and supervisors), as well as for large unskilled labor force [1]. Although most of these jobs can be replaced by IoT and artificial intelligence (AI) technologies, integrating Vertical Farms will still affect urban employment.

## **4. Engagement**

There are numerous ways to contact potential clients to establish vertical farms. The initiator may use tools like local government programs and broadcasting to spread the word. These avenues could get the attention of governments and possibly result in idea evaluation and financing down the road. Using contemporary resources like business incubators and accelerators, as well as crowdfunding platforms, is the other practical way to address this question [18].

Crowdfunding sites are crucial in helping entrepreneurs launch their businesses, allowing them to obtain capital from a big pool of investors and promote their new enterprise to a broader audience. Startup accelerators, nevertheless, are short, intensive programs focused on providing early- or mid-stage entrepreneurial tools, instructions, and mentoring. Often cohort-based, accelerators are more organized and offer particular courses to help one's firm grow into a scalable business. Incubators provide the spaces and tools necessary to support the initial idea, while accelerators condense years of study and development into a few months [19].

The second thing entrepreneurs should be concerned about after starting a vertical farm is maintaining the flow of capital and clients. Delivering vital information to clients, including a transparent report, project accomplishments and problems, and a clear exit plan for future development, should be the main focus of this phase [20]. Through this performance, investors and businesses will develop a sense of trust. Moreover, companies should attract them with consistent returns to make financiers invest further. Additionally, giving certain advantages, like early access to investments and product purchases, would keep customers interested in the firm.

## **5. Foundational operational pillars**

An indoor farm's location selection significantly impacts its infrastructure and operations. In areas where land costs are prohibitive, vertical farms can be carefully positioned in underutilized locations such as abandoned buildings, subterranean passageways, or areas beneath overpasses [21]. Vertical farming systems have the potential to be implemented in a variety of locations. However, water supply and temperature-control (cooling or heating) costs might differ significantly based on the particular environmental context and conditions.

The success of indoor vertical farming dramatically depends on the effective use of technology. Automation, sensors, and LED lighting are just a few technological advancements that have revolutionized indoor agriculture, making it more efficient in meeting the demand for specific crops [21]. Crop production in vertical farms depends critically on lightning, particularly artificial lighting, such as LEDs that take the place of natural sunlight [22]. As a result, elements such as spectral quality and light intensity profoundly impact plant growth and development, improving their nutritional value and controlling essential functions [23]. Among artificial lighting options, LEDs are the most promising artificial lightning alternative available today for horticulture in controlled environments because they are stable, long-lasting, and can adjust to a specific light spectrum [24]. Although vertical farming demands higher efficiency (i.e., 50–60%), for cost-effectiveness, standard LED technology achieves only 28% [2].









Nonetheless, the capacity of LED-based lighting is becoming more capable, especially with color-mixing technology [25]. With real-time sensors, vertical farming

systems offer precise monitoring and control of growth conditions. Through software or firmware applications, using big data and Internet of Things (IoT) technology can lead to enhanced crop-production knowledge, such as LED lighting and nutrient formulation. Continuous monitoring systems produce big data to optimize resource use, save costs, and improve plant quality [24]. Moreover, stored in sensor networks, these data help create AI algorithms for the most efficient and effective growth recipes [26].

Automation combined with IoT, at the same time, can save expenses and human labor involvement. Actuators are other essential components of vertical farming because they provide precise control over various aspects of the environment. These devices convert electrical inputs into mechanical movements, enabling dynamic modifications that maximize plant development. Actuators are crucial in managing irrigation systems, airflow regulation, and lighting placement [3]. By regulating and maintaining consistent air quality and temperature, actuators create a vital environment for healthy plant development. Actuators also automate irrigation processes by regulating pumps and valves to supply water to plants precisely, minimizing waste and guaranteeing steady hydration, thus enhancing water management efficiency. Implementing actuators in vertical farming improves responsiveness, accuracy, and resource optimization, enhancing plant growth and overall farm production [27]. **Table 1** highlights the fundamental features and uses of essential actuators in indoor farms.

The feasibility of this system mainly depends on the application of modern technologies, including vertical growing systems, LED lighting, automation, and IoT, among others. The current efficiency of modern LED lighting systems is approximately 28%; however, it can be increased up to 50–60% at present, and it also attacks the so-called optimized light spectrum that accelerates plant growth and yields [3]. Besides photosynthesis enhancement, this technology also helps to provide better resource utilization, including light, by minimizing wasteful use. Also, automation and IoT make the functioning of vertical farms much more effective and operative. Sensors and actuators also allow for the real-time management of the environment within the structure, including temperature, humidity, and nutrient levels that, in turn, will boost the plant's health and minimize waste production [28]. Thanks to these technologies, in conjunction with big data analysis, one can improve the recipes for growth, thus making the processes in vertical farming more productive and effective. **Table 2** below compares specific crop growth in vertical and conventional agriculture.

Overall, in vertical farming, the extent of efficiency is geared toward applying sophisticated technology in automation and sensors. Some key technologies are the real-time sensors required for measuring the state of plants and the environment and actuators, which allow for controlling the water and climate supply [30]. These technologies afford suitable growing environments, enhancing productivity and utilizing the available resources. For example, big data and IoT incorporated in the business empower constant examination and accumulation of data, which are used to adapt development recipes and enhance yield quality. Besides, the concept of energy management is fundamental; vertical farms of today's world include eco-friendly mechanisms, including LED lighting systems that are adjustable for spectral quality and intensity for photosynthesis [31]. The nature of these technologies associated with vertical farming can be further elaborated on with the help of additional data regarding such specifics of the equipment as the models of sensors, as well as the software for the analysis of the data gathered in the functioning of the vertical farming systems.

Item	Type	Specification	Applications	Image
	Heater	<ul style="list-style-type: none"> <li>Power input: 110, 220 V; Power: 2.8 kW</li> </ul>	<ul style="list-style-type: none"> <li>Used to increase ambient air temperature.</li> </ul>	
	Cooler	<ul style="list-style-type: none"> <li>Power input: 110, 220 V; Lowest temp: 0 °C; Coverage: 450 m<sup>2</sup></li> </ul>	<ul style="list-style-type: none"> <li>Used to decrease ambient air temperature.</li> </ul>	
	Humidifier	<ul style="list-style-type: none"> <li>Power input: 110, 220 V; Coverage: 2000 m<sup>2</sup>; Power: 2.2 kW</li> </ul>	<ul style="list-style-type: none"> <li>Used to increase ambient air humidity.</li> </ul>	
Aquators	Dehumidifier	<ul style="list-style-type: none"> <li>Power input: 110, 220 V; Humidity removal: 2.5 L/h Air flow rate: 30 m<sup>3</sup>/h; Coverage: 50 + 100 m<sup>2</sup></li> </ul>	<ul style="list-style-type: none"> <li>Used to decrease ambient air humidity.</li> </ul>	
	LEDs	<ul style="list-style-type: none"> <li>Power input: 110, 220 V; Light intensity: 17,400 flux; Output: 300 W</li> </ul>	<ul style="list-style-type: none"> <li>Used to supply plants with the desired light intensity.</li> </ul>	
	Fan	<ul style="list-style-type: none"> <li>Power input: 110, 220 V; Air flow rate: 4400 m<sup>3</sup>/h Output: 1.1 kW, 437 rmp</li> </ul>	<ul style="list-style-type: none"> <li>Used to circulate the ambient air.</li> </ul>	
	CO <sub>2</sub> regulator	<ul style="list-style-type: none"> <li>Power input: 110, 220 V; Flow rate: 0.5–15 SCH-Control type: Digital, solenoid</li> </ul>	<ul style="list-style-type: none"> <li>Used to maintain the target CO<sub>2</sub> level inside the growth chamber.</li> </ul>	
	Nutrient pump	<ul style="list-style-type: none"> <li>Power input: 110, 220 V; Maximum flow: 100 L/min Maximum head: 24 m; Power: 0.75 HP / 0.55 kW</li> </ul>	<ul style="list-style-type: none"> <li>Used to supply nutrient solutions to the root zone of plants.</li> </ul>	

Kabir et al. [27].

**Table 1.** Fundamental features, usability, and applications of most used actuators in vertical farms.

Resource efficiency	Vertical indoor farm (10 layers of lettuce)	Conventional outdoor cultivation (lettuce)
Efficiency of water use	1 l/kg/year	250 l/kg/year
Water consumption	Usually hydroponics or aeroponics approx. 11 l/head	Irrigation and precipitation approx. 250 l/m <sup>2</sup>
Energy use/consumption	250 kWh/kg/year	0.3 kWh/kg/year
CO <sub>2</sub> emissions	158 kg/t lettuce	540 kg/t lettuce
Light source	Artificial lighting operating 10–24 h/day	Sunlight
Use of crop protection products	Indoor cultivation sterilized environment	Use of EPA-approved pesticides, herbicides and fungicides, as well as traditional methods such as plowing, weeding and mulching
Yield	80–120 kg/m <sup>2</sup> /year	3.9 kg/m <sup>2</sup> /year
Land use	365 days/year	275 days/year
Efficiency of land use	0.3 m <sup>2</sup> for 1 kg/day	93 m <sup>2</sup> for 1 kg/day
Harvests per year	8–12 per year	2 per year
Transport distances	43 km	3200 km

*Modified by Snigur according to: Avgoustaki and Xydīs [29].*

**Table 2.**  
 Resource efficiency of lettuce cultivation in vertical farming and conventional farming in comparison.

## 6. Strategic collaborations

There are clear advantages for current distributors of fruits, vegetables, and food when they collaborate with vertical farms. Year-round crop production allows distributors to grow their network and substantially boost their revenue. Moreover, it protects demand, minimizes resource consumption, and utilizes existing channels. Furthermore, a food business can increase the diversity of products by obtaining fresh produce from its associates. This helps retailers satisfy consumer demand for locally produced, pesticide-free food while enhancing the quality and flavor of their fresh products. Crucially, merchants may shorten their supply chain by collaborating with investors or other businesses to establish vertical farms. It is not a secret that long or complex supply chains can be unstable, particularly when the food has a limited shelf life, as with fruits and vegetables. These days, supply chain disruptions and delays are typical, which results in more waste followed by more expenses and fewer products on the shelves [32]. Food stores, nevertheless, may supply themselves with their product, avoid the risk of drawn-out supply chains, and cater to a growing market by partnering with vertical farms.

By collaborating with expanding vertical farms, investors, financial partners, and governmental and non-governmental organizations may profit from the evolving agrotech industry. Investors can get in early to support growth and benefit from established success at smaller venues. The EU has already confirmed its intention to significantly reduce the usage of pesticides in agricultural production, with a target of 50% cut by 2030 [33]. The increasing customer desire for food free of pests indicates a developing market that the vertical farm concept can meet. While increasing the demand for pesticide-free products is one of the reasons for investing in them, there

are several others. The relatively low startup and operational costs make vertical farms feasible for all kinds of investors. Due to the trend of green investments, an increasing number of people and companies are looking for alternatives to investing in organizations, goods, or sectors of the economy that are known to harm the environment. A vertical farm partnership may produce substantial and sizable returns in addition to meeting the criteria of a green investment [20].

It is certainly appealing for existing agro-technologies distributors and resellers to collaborate with vertical farmers, investors, retailers, and entrepreneurs [8]. Instead of simply selling their technological innovations to farmers and companies, they can establish enduring professional connections with individuals and institutions inside their target market. By doing so, they may maximize their profitability and increase customer flow. Nevertheless, this partnership offers advantages beyond only increased profits. This alliance will create the opportunity to raise brand recognition in the sector and position the company as a market leader. Working directly with farmers and gaining in-depth knowledge of the type of technology they require is another advantage of a partnership. In doing so, agro-tech companies will consistently enhance and evolve their technologies to deliver effective and efficient solutions.

The overall concept of strategic collaborations in vertical farming is very lucrative, as seen in successful examples, including InFarm, which partnered with the EDEKA, which has over 1000 vertical farming units installed in the stores, cutting down on the carbon footprints and expanding the market share [34]. On the other hand, AeroFarms partnered with Dell Technologies to enhance IoT's data analytics and incorporations, which resulted in smart planting and resource utilization. Another example is when in Singapore, Sky Greens partnered with Singapore's FairPrice so that they were always assured of a ready market by selling fruits and vegetables that were sourced locally and grown nearby, thus meeting their sustainable agenda best [35]. Some strengths are resources/innovation, while some weaknesses are risks and dependency on regulation. However, the strategic partnership holds high potential in growing the market, improving the ability, and catering to the sustainability procedures that are crucial for the growth of the vertical farm industry.

## **7. Cost structure and revenue stream**

When starting a vertical farm, securing an appropriate location and obtaining the required equipment are two main startup expenditures [36]. For example, for the iFarm (a vertical farm company), the cost per square meter to outfit an area with their rack technology, including setup and activation, is around \$1000 (the exact cost varies based on the farm's size and the structure's state). The total capital expenditure (CapEx) for a 1000 sqm growing area (500 sqm of floor and 4.5 meters of height) would be roughly \$1 million; this includes equipment and installation but excludes building constructions, logistics, and customs fees. Running a large-scale vertical farming operation is financially and technically demanding; the most significant expenditure is energy.

Energy use for rack construction is high, especially for LED lighting, which can account for half to two-thirds of the energy bill. The final third part of the bill is influenced by continuous humidity management and climate control, which include dehumidification and air conditioning. The energy needed for other farm management tasks like automation usually makes up less than 10% of the total expenses. The location, size, and kind of technology employed in indoor farming processes

determine the electricity expenses. A farm with a total cultivation area of 1000 sqm using iFarm Leafy Greens technology, for example, would cost \$8600 a month in Norway, \$3500 in Saudi Arabia, and around \$2000 in Qatar, based on its daily use of 1705 kW [36]. The efficiency of LED bulbs, the need for agricultural lights, and possible government subsidies are further considerations that could affect the electricity price. Cutting down on electricity and energy bills can be done by choosing automated solutions over conventional ones.

Moreover, for agricultural businesses, recruiting highly skilled workers might account for as much as 60% of their operating costs. Labor needs are determined by the degree of automation, where high levels of automation reduce operating expenditures (OpEx) in the long term while raising initial CapEx. For instance, labor expenses for a 1000 sqm vertical farm in Saudi Arabia will add up to \$13,000 monthly for manual labor but 30% cheaper for the same size automated farm. In European countries, it may be twice as high. Automation is, therefore, a critical factor in labor costs and must be considered for farms to be profitable.

Vertical farming requires more investments to set up, with costs for equipment alone ranging from \$500,000 to \$ 4 million per acre, but operational costs like energy will be \$200,000 per year, but the yields and incomes that will be accrued from vertical farming will far outweigh that of conventional agriculture [20]. Traditional farming has lower initial costs, ranging from \$ 1000 to \$2000 per acre, compared to modern agriculture, which is less efficient and subjected to environmental conditions [37]. Vertical farms can yield between 4 and 20 times as much per acre and can fetch high market prices due to factors such as freshness, location, and pesticide-free produce; the revenues could amount to \$1.2 million to \$2.4 million annually for a 10,000 square meter facility [29]. This is far higher than the \$30,000 to \$50,000 revenue produced in traditional farming for the same area. Coupled with up to 95% water sparing and less emission of greenhouse gases, vertical farming is economic and ecological.

It is essential to make a personalized approach in computing to figure out the CapEx, OpEx, return on investment, and payback periods [20]. However, to provide an example, let us look at a vertical farm business powered by iFarm Leafy Greens technologies in the United Arab Emirates. The cultivation area of a 1000 square meter farm brings in \$57,800 a month in revenue with an output of about 3400 kg of food. Approximately \$32,600 is spent each month, yielding earnings before interest, taxes, depreciation, and amortization (EBITDA) of \$25,200. Within the typical payback period of 4–6 years, the investment in iFarm technology is anticipated to be recouped in 3.6 years. The computation, which notably leaves out costs for construction, remodeling, and import taxes, emphasizes the significance of conducting in-depth market research.

## **8. Brief advantages/disadvantages of vertical farming**

Compared to conventional irrigation methods, vertical farming is an innovative approach that minimizes water waste by 95%, whereas traditional farming uses up to 70% of freshwater to produce food. Moreover, it also minimizes soil degradation while offering exceptional space efficiency. The key benefits include year-round production, crop growth conditions, and freshwater recirculation [38]. These indoor farms reduce labor and transportation costs by implementing advanced technologies. However, one should consider several challenges requiring strategic resolutions, most notably high costs when realizing vertical farms. Installing and maintaining

the vertical farming infrastructure, which consists of automated systems, advanced lighting, and chambers with regulated environments, can be costly to establish and sustain. The primary factor of concern is the energy used, particularly from photosynthetic LED lighting [27]. However, these disadvantages of vertical farming can be overcome by future development of renewable energy sources, using LED in plant growth, and automation of the vertical farming system.

Although renewable energy has its advantages in this case, it may not always guarantee total farm self-sufficiency, especially if there are some incompatibilities with specific setups. In contrast, while climate-related issues impacting crop yields make it difficult for traditional agriculture to meet the growing global food demand, optimizing farming methods for the sustainability of these farms might increase their efficiency despite adverse environmental effects [39]. As an immediate shift to vertical farms is almost impossible, gradually implementing low-carbon farming methods would potentially align with increasing food needs sustainably.

## **9. Conclusion**

Concluding, urban vertical farming is becoming more feasible due to recent technological advancements such as robots, sensors, and AI. These technologies have transformed agriculture by enabling data analysis, automated operations like harvesting, and monitoring plant developments and disease, reducing the need for human engagement and ensuring the industry's viability in urban settings. However, continual technology improvements and competitive changes are the reason for the lack of industry-wide standardization and sustainability certifications in vertical farms. Establishing industry standards would simplify evaluating performance and distributing innovations across vertical farms. Despite these drawbacks, vertical farms may support the local economy, reduce hunger, and create advanced environmental initiatives. The success of vertical farming highly depends on handling a variety of geographical conditions. Climate, technology, economic conditions, cultural practices, and governmental support all contribute to the challenges and opportunities that vertical farming projects worldwide.

Urban vertical farming can now become more feasible with the support of robotics, sensors, and AI technologies that help control plants and automate many processes. Thus, for the governmental decision-makers, it is critical to work on creating industry standards and certification to enhance coherency and stimulate contemporaneous development. Investors should look at vertical farming as a promising field that can reward them well from their investment point of view and endorse the move toward formulating guidelines. Experts should also be prepared to apply the available technology and discuss ways to improve it with other professionals to mitigate the sector's geographical and climate-related issues. Further studies, the application of technology, and international collaboration will help eradicate the current disadvantages and enhance the opportunities for vertical farming.


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Section 2

Innovations in Technology  
and Intelligent Solutions

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## Chapter 3

# Unlocking the Potential: Artificial Intelligence Applications in Aquaculture Greenhouse Development

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### Abstract

Aquaculture plays a significant role in the expanding agricultural sector, with historical challenges stemming from experimental limitations. Upholding ecological balance and water quality improvements stands as a pivotal factor in bolstering the efficiency and sustainability of aquaculture production. Notably, aquaculture greenhouse setups have addressed various environmental concerns, boosting productivity and sustainability. The ongoing advancement of science and technology has ushered in a new era in aquaculture, marked by the integration of Artificial Intelligence (AI) and digitalization. AI represents fascinating and powerful machine learning-based techniques for solving many real-world problems. To regulate water quality in aquaculture, AI is used to assess sensor data in real time using sophisticated algorithms, allowing for proactive adjustments to maintain ideal conditions. Likewise, AI is essential to disease identification since it uses the Internet of Things (IoT) and machine learning (ML) models to identify subtle patterns in fish behavior or health parameters, facilitating early intervention and mitigation strategies. This book chapter overviews the transformative role and potential applications of AI in the development of aquaculture greenhouse systems, including environmental monitoring, feed management, disease detection, predictive analytics, data collection, model development, and ethical considerations. By unlocking the potential of AI, aquaculture greenhouse development can benefit from increased productivity, reduced environmental impact, and enhanced sustainability.

**Keywords:** smart aquaculture, IoT, ML, sensors, AI, machine learning, algorithms, aquaculture sustainability

### 1. Introduction

Aquaculture has evolved into a critical pillar of the world's food supply and economy. With the growing demand for seafood, aquaculture is essential for meeting

this need sustainably. The projected rise in the global population to 9.7 billion by 2050, an increase of 2 billion individuals, underscores the significance of aquaculture in providing food security [1, 2]. This increase underscores the imperative to enhance food quality and upgrade existing food production systems [3, 4]. Aquaculture has emerged as a vital pillar of global food security over the last two decades, employing intensive farming techniques across a variety of species, offering high controllability, and demonstrating market adaptability to meet the escalating food requirements [5]. By 2024, it is anticipated that global aquaculture output will hit 122.6 million tons, with 71% attributed to aquatic animals, valued at US\$264.8 billion [6]. In the face of shifting environmental conditions, fish farming is encountering new challenges. Factors such as fluctuating water availability, influenced by changing rainfall patterns or rising temperatures, pose significant risks to aquaculture operations [7]. This necessitates a heightened focus on environmental monitoring and control to ensure the sustainability of future fish farming practices [8]. Emerging biosecurity threats like parasites and diseases emphasize the appeal of closed aquaculture systems to producers. Monitoring and control technologies play a key role in this context, enabling the automated regulation of various parameters such as oxygen levels and equipment status through sensor data aggregation [9]. However, traditional aquaculture practices have faced challenges related to environmental impact, production efficiency, and sustainability [4, 10]. Due to these challenges, the development of aquaculture greenhouse smart systems has emerged as a promising solution to address these issues. The future of aquaculture lies in smart technologies, including IoT, ML, sensors, and AI, which will not merely be an option but a fundamental challenge for industry practitioners to embrace. Adapting to this paradigm shift will be essential for success in an increasingly competitive and globalized world, where those adept at navigating the fourth industrial revolution will have a distinct advantage [11].

Aquaculture greenhouse systems represent a modern approach to aquaculture that integrates controlled environment agriculture techniques with traditional aquaculture practices [12]. These systems provide a controlled and optimized environment for aquatic species, offering benefits such as enhanced production efficiency, reduced environmental impact, and improved sustainability. By utilizing greenhouse structures, aquaculture operations can better regulate key environmental factors such as temperature, light, water quality, and nutrient availability [13]. This level of control allows for increased productivity, faster growth rates, and improved disease management compared to open-water aquaculture systems. Aquaculture greenhouse systems also offer the potential for year-round production, regardless of external weather conditions, further increasing the reliability and consistency of output [14]. In the future, all terrestrial fish and crustacean farms will transition to Smart Farming, driven by Information and Communication Technologies (ICT). This shift will empower aquaculture farmers with precise, real-time insights into their operational environment and livestock, moving away from reliance on empirical methods toward data-driven decision-making [15]. By integrating sensors to monitor essential parameters like dissolved oxygen, temperature, and feed requirements, farmers can gain a comprehensive understanding of their stock's needs and development [13].

Advancements in technology allow for an expanded range of parameters to be controlled within a farm, emphasizing the need for farms to prioritize maximum profitability while minimizing costs. Utilizing sensors enables farmers to pinpoint peak feed demand hours, monitor consumption patterns, and assess the impact of oxygen and temperature variations on livestock behavior. Analyzing this data systematically

can drive continuous improvements in production [16]. While there is still time to embrace this transformation, achieving a 4G aquaculture model will not be without hurdles. Key challenges include delivering higher quality products, optimizing efficiency, enhancing performance, and implementing preventive maintenance practices [17]. To navigate the shift toward smart aquaculture successfully, the industry must attract new ICT talents, upskill existing personnel, restructure organizations to accommodate new roles, bolster cybersecurity measures, and ensure farms have access to advanced connectivity technologies like 4G and eventually 5G [18]. Smart aquaculture, including IoT, ML, sensors, and traditional aquaculture practices, has the potential to mitigate risks, enhance product quality, and boost fish fry survival rates, thereby fostering sustainable industry growth. Economically, reducing the costs associated with implementing AI will be crucial for widespread adoption, as many companies view this as a significant barrier to digital transformation [19].

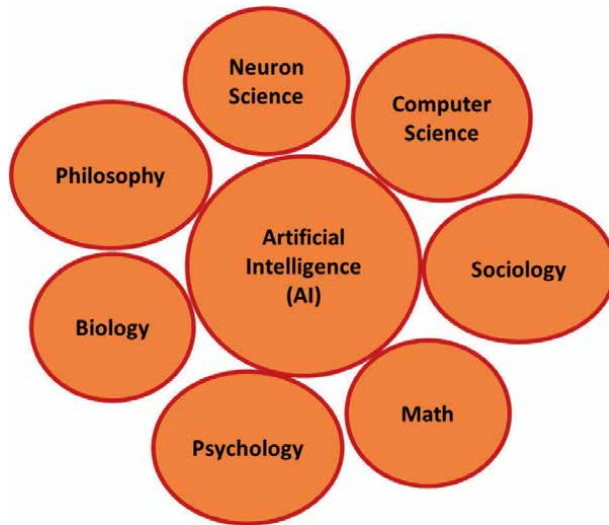
This chapter aims to explore the transformative role and potential applications of AI in the development of aquaculture greenhouse systems. By delving into the intersection of AI technology and aquaculture practices, this chapter will provide insights into how AI can unlock the full potential of aquaculture greenhouse development.

## 2. AI: An overview

AI entails the capacity to entertain conflicting ideas yet maintain functionality. AI must encompass learning from past experiences, employing reasoning in decision-making, leveraging inference capabilities, and delivering rapid responses [20]. Moreover, it should be equipped to prioritize tasks, navigate complexity and uncertainty, and make decisions akin to human intelligence. Machines endowed with AI can perform tasks that typically necessitate human intelligence. The scientific objective of AI is to comprehend intelligence by constructing computer programs that exhibit intelligent behavior through symbolic inference or internal reasoning processes [21]. Therefore, the definition of AI is contextual and evolves, considering the system's effectiveness in the current era [22]. However, AI finds diverse applications across various domains [23–25], as the following: (a) It is utilized for designing and evaluating mechanical components based on size constraints, (b) AI can diagnose electronic locomotion systems effectively, (c) Application in electronics and electrochemical systems is feasible, (d) It aids in diagnosing the software development process efficiently, (e) AI is proficient in identifying chemical compound structures and compositions, (f) AI assists in planning experiments in fields like biology, chemistry, and genetics, (g) It plays a role in creating stock and bond portfolios for selection and management, (h) Troubleshooting systems benefit from AI integration, (i), AI contributes to space exploration and planning, and (j) Forecasting crop damage is another application of AI.

**Figure 1** illustrates how these disciplines intertwine to shape both the theoretical underpinnings and real-world implementations of AI. At the core of AI exploration and advancement is the improvement of computer functions linked to human intelligence, including reasoning, learning, and problem-solving. Progress in these domains enables AI systems to undertake activities that historically demanded human cognitive skills, fostering novel applications across various sectors and fields [26, 27].

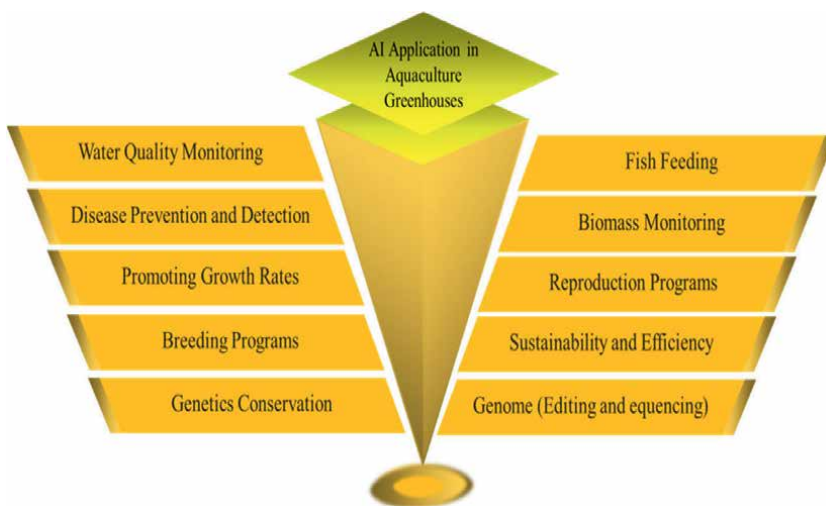
The field of AI encompasses various components that aim to emulate human intelligence through computational means [28, 29]. These components include:



**Figure 1.**  
*Artificial Intelligence Sciences.*

### 3. AI potential applications in aquaculture greenhouse systems

The aquaculture greenhouse industry is rapidly expanding and requires significant technological advancements to enhance farming practices [30]. Developing innovative farming methods is crucial for increasing productivity, with AI playing a pivotal role. AI tools are now more accessible, providing a stable environment for aquatic stock [31]. While numerous applications of AI may be utilized in aquaculture greenhouses, we will discuss deeper into a few specific examples below (Figure 2).



**Figure 2.**  
*Potential applications of artificial intelligence in aquaculture greenhouse systems.*

### **3.1 Water quality monitoring**

Ensuring water quality is paramount in aquaculture, as it has a direct impact on fish well-being and production efficiency. The integration of Artificial Intelligence (AI) is increasingly prevalent in this domain to streamline monitoring processes [32]. AI utilizes sensor data that monitors important variables such as temperature, salinity, dissolved oxygen, pH, and ammonia levels to identify trends and irregularities indicative of water quality issues [33–35]. Specifically, AI algorithms can process information from temperature sensors installed in fish farms to provide continuous monitoring of water temperature. This enables timely corrective actions, reducing the risk of fish harmful. AI-driven systems offer real-time monitoring, providing accurate information swiftly compared to manual methods [36].

Moreover, AI can optimize water quality parameters based on specific fish species requirements. Researchers have developed AI models for water quality index prediction and classification, employing techniques like artificial neural networks and machine learning algorithms to enhance aquaculture water quality management [37–39]. Their findings demonstrated that the proposed models can effectively forecast the Water Quality Index (WQI) and categorize water quality with high reliability [40]. Additionally, temperature plays a crucial role in aquaculture, directly influencing the well-being and development of aquatic organisms.

This approach enables the system to recognize patterns and deviations in temperature data, promptly notifying farmers when temperatures stray from the optimal range for the specific type of fish being raised [41]. This makes it possible to identify temperature changes quickly and to take the necessary action to maintain the ideal circumstances for fish growth and health. AI systems that continuously monitor temperature can also help farmers anticipate possible problems caused by temperature variations and provide insightful information on how environmental changes affect fish [38, 42]. Additionally, AI algorithms are capable of analyzing data from a variety of environmental elements, such as weather patterns, feed management, and water quality, to provide a thorough picture of the state of the fish farm [30]. AI algorithms that combine this data can provide farmers with more accurate and comprehensive insights into the ways that various environmental factors can affect the growth and health of fish. This gives farmers the information they need to improve their fish farming methods and avoid problems that could arise from changes in temperature or other environmental factors. These studies' findings imply that AI systems can provide fish growers with useful advice [31]. In the aquaculture industry, AI plays a crucial role in predicting fish health by analyzing environmental data such as water quality parameters like temperature, pH, OM, EC, and DO [43]. By applying AI algorithms, deviations from normal conditions can be identified early, enabling proactive measures to maintain fish well-being [44].

### **3.2 Fish feeding**

In aquaculture, the cost of feeding fish constitutes a substantial portion, ranging from 40 to 50% of the total operational expenses [45, 46]. Furthermore, approximately 60% of the feed dispensed in aquaculture settings is converted into particulate matter, underscoring the importance of efficient feeding practices [47, 48]. These collected particles contaminate the water by using oxygen to disintegrate and emitting toxic compounds such as ammonia and nitrogen, which can impair fish growth. Fish production is greatly increased when feed is given following fish demand levels, even

if measuring fish feed intake remains a substantial challenge [49]. By figuring out the best feeding schedule and portion size, AI can optimize fish feeding. This optimization may increase fish growth and health, reduce waste, and improve feed efficiency [50]. AI holds significant promise in the realm of aquaculture feeding optimization, where it can profoundly influence fish behavior, appetite, and growth rates [51]. By reducing waste and reducing the chance of overfeeding, this strategy can shield the ecosystem from the negative effects of contaminated water. An AI model may be trained with real-time sensor data to precisely estimate aquatic animals' biomass and calculate the right amounts of feeding [52]. AI is also capable of evaluating fish behavior and hunger in real time, besides refining feeding schedules. Cameras and sensors can monitor activities like feeding, swimming, and signs of stress or hunger, ensuring fish receive the precise nutrition required for their growth and development by adjusting feed schedules and quantities on the fly [31]. Research indicates that AI can create personalized feeding plans for individual fish, factoring in their genetic makeup, age, and body weight [50]. Precision aquaculture, geared toward maximizing growth rates and mitigating the environmental impact of aquaculture activities, reaps substantial benefits from AI-driven feeding optimization [53].

The fish-feeding system is generally classified into three categories: manual method, semi-automated method, and automated method. In the manual feeding method, the feeding process is directly operated by a person. It involves the use of techniques such as fish body weight per feed [54, 55], estimation of facial and metabolic waste output, feed conversion rate, and bio-energetic data at different water temperatures. This method seems to be sufficient means to manage the amount of feed dispensing as a result of user involvement. However, it is time-consuming, labor-intensive, and not applicable to a large fish farm [56]. The semi-automatic system uses electronic components such as digital timers and programmable timing to dispense feed according to the user's predetermined timing. To complete a feeding task, this system necessitates a certain level of user involvement. Developing a semi-automatic fish-feeding regime system is mostly accomplished through the use of digital timers and programmable timing [54]. An automatic fish feeder with a digital timer was suggested by Ogunlela [47]. For precision timing circuits that can provide exact oscillation or timing delay, the timer was set up with monostable and astable modes. In the monostable operation mode, the time interval was controlled by a single external resistor and a network of capacitors, whereas the operation time and one-short pulse generation were computed between 1 and 10 seconds in the astable mode. A digital timer was a key tool used by Uddin et al. [57] to control the system's operating duration when they designed a 24-hour time-step fish feeder. The volume of feed delivered and the time interval for both 4 mm local and foreign vital (feeder) were determined by testing the designed system. According to the data obtained after 60 minutes of operation, 85.5 kg of the meal was given to the aquarium, and the feed loss was less than 3%. This makes it possible for the system to manage and preserve feed under stringent conditions with an 86.9% adequacy and efficiency. A recent study by Niswar et al. [58] used a microcontroller unit to develop an autonomous fish-feeding system for softshell crabs. To prevent food waste, their method called for pre-defining 5% of the crab's body weight to be dispensed at each activation time. The amount of food dispensed and the predetermined amount differed by 0.05 to 0.1 g, according to the results. Implementing this type of feed distribution system is simple. According to the report, the majority of feeding regime systems currently in use are made to run at predetermined times. The automated approach, as the name implies, entirely accomplishes the feeding operation without human interference. This approach makes use

of technologies like fuzzy logic controllers (FLC) and computer vision (CV). An automated feeding regime system based on the CV for indoor intensive rearing of eels was proposed by Chang et al. [59] Using an infrared photoelectric sensor, the study sought to ascertain fish appetite by observing the eel's gathering behavior. The system was intended to come back to life at a certain time. The feeder was supposed to halt until the next rouse if the sensor failed to detect the eel collecting for three consecutive tries. As a result, it reduces the possibility of a high rate of feed waste. This strategy, however, is ineffective and unreliable since the system keeps working based on collecting fish without first determining its goal, which could result in additional issues. The best strategy should be a system that is managed according to the eel's real feed intake or its capacity to ascertain the goal of gathering. Furthermore, the mechanism should only activate when the eels are hungry, not only after a predetermined amount of time. Soto-Zarazúa et al. [60] controlled the diet given to tilapia by taking into account body weight, temperature, dissolved oxygen, and fish age. Because these factors directly affect fish development and metabolism, a fuzzy-logic control algorithm based on the above parameters was used for fish feeding.

### **3.3 Disease prevention and detection**

AI is essential for improving the welfare and health of fish raised for food since it helps detect and manage diseases. Numerous researches have examined how AI can supervise fish spawning, improve feeding schedules, and identify and treat illnesses. AI is being utilized more and more in aquaculture to identify and treat fish illnesses [61]. AI is capable of identifying symptoms of disease or stress in fish by evaluating data from sensors and cameras. For example, cameras can watch fish behavior and pick up on changes like decreased activity or strange swimming patterns that could point to illness or stress. According to Chen et al. [51], advanced disease identification based on fish behavior and appearance is a promising use of AI [62]. An additional technique for identifying illness markers in fish photographs is to analyze them. AI can predict fish health in aquaculture by evaluating environmental variables including dissolved oxygen concentrations, pH levels, and water temperature [44, 63]. The early detection of these parameters, which may indicate health problems in the fish population, is possible through the use of AI and IoT [63]. Additionally, the behavior of fish and physical traits can be observed for indications of illness or distress using image recognition techniques, allowing for timely intervention and efficient disease control in aquaculture systems [41]. AI can identify indications like lesions, strange behavior, or discoloration by looking at photos taken by farm cameras. AI can also help detect fish infections through the analysis of water quality data [64, 65]. Fish health can be affected by illness presence, which can be revealed by variables such as temperature, pH, and dissolved oxygen levels. AI systems are capable of analyzing data on water quality to spot patterns that point to disease outbreaks [66]. AI algorithms that evaluate environmental conditions can forecast when and where diseases may occur, enabling aquaculturists to take preventative action to stop the spread of the disease and financial losses [67, 68].

AI-driven image recognition techniques can be employed to monitor fish behavior and physical characteristics, facilitating the early detection of abnormalities or signs of disease [69]. This comprehensive approach allows for timely interventions and effective disease management strategies within aquaculture systems [70]. Additionally, AI can help in early interventions, reducing antibiotic use by adjusting water quality indicators or providing tailored treatments. Some studies have explored

using AI to analyze video data from salmon farms to detect behavioral changes indicating stress or disease. Researchers have employed deep learning algorithms to identify fish behavioral patterns and detect early disease signs accurately [71]. This shift toward intelligent aquaculture practices using AI has the potential to significantly improve fish health and well-being in aquaculture settings. While current techniques show promise, more research is necessary to explore AI's full potential in aquaculture and develop more sophisticated algorithms and models [72].

### **3.4 Biomass monitoring**

Evaluating the well-being and development of fish during their growth phase hinges on their biomass. The conventional technique for gauging biomass entails physically capturing each fish, individually weighing them, and then summing up their total weight. This method is laborious, demands considerable effort, and proves challenging when handling a substantial number of fish samples for precise estimation [73]. Moreover, human errors frequently result in measurement inaccuracies. Manually managing fish in this manner can induce stress in the fish, potentially leading to growth impediments, nerve damage, or even mortality. Additionally, handling deceased fish during subsequent processing stages can impact the quality of the final fish product. To overcome these obstacles, researchers have delved into alternative approaches for estimating fish biomass [74]. The utilization of artificial intelligence (AI) brings fresh opportunities for modernizing aquaculture practices. By amalgamating machine learning and computer vision, more accurate techniques for determining fish weight can be devised. Machine learning and computer vision have emerged as potent tools in various domains, showcasing their potential in fisheries management and environmental surveillance [75].

Numerous studies have explored the application of machine learning algorithms to refine the precision of fish weight estimation. One effective strategy involves leveraging computer vision methodologies to scrutinize fish images and extract pivotal features for forecasting their weight. For example, the study conducted by Lopez-Tejeida et al. [76] improved a technique for ascertaining fish weight utilizing machine learning alongside a near-infrared (NIR) camera featuring a Haar Cascade Classifier. Their findings revealed that through integrating hardware and software enhancements, such as incorporating infrared light and a pass band filter to the camera, fish could be automatically identified, and their weight and length accurately computed, even foreseeing their future weight. The measurement of body lengths of harvested fish serves as a crucial indicator for marine resource management. Various fisheries management bodies mandate fishing vessels to report the lengths of the fish caught [77]. Traditionally, fish body lengths are manually measured using rulers or tape measures. However, such methods are time-consuming, labor-intensive, and subject to subjective interpretations. Several researchers have delved into algorithmic research on fish size estimates utilizing datasets like ImageNet and the Atlantic fish dataset. For determining the length of European bass across different architectures, Monkman et al. [75] recommended the R-CNN model. The author also utilized OpenCV to analyze the images and enhance accuracy considering image distortions. The findings indicated a typical deviation percentage of 2.2%. Presently, one of the primary methods for discerning fish age involves the automatic interpretation and recognition of fish age through otolith images [78]. Machine learning has proven effective in tasks

such as object recognition and various forms of image analysis, playing a crucial role in otolith image-based age estimation. To ascertain fish age, Moen et al. [79] employed deep learning to automatically interpret otolith images and transfer ImageNet pre-trained parameters to the trained CNN model via transfer learning. Experimental results demonstrated the model's strong performance, enabling comparisons with the accuracy of human experts. However, the model exhibited challenges in accurately predicting the age of the youngest fish, leading to lower prediction accuracy for specific age groups. In the realm of fish sex identification, historical methods relied on biological techniques that often led to high detection errors and inflicted trauma on the fish. Machine learning-based approaches for sex determination focus on the relative morphological parameters of the fish rather than the fish's quality or age. Machine vision technology can effectively capture the morphological parameters of fish, making the combination of machine vision and ML a potent method for efficient fish sex identification [80–82]. Using the Random forest algorithm and Boruta algorithm, Barulin [83] studied the sex identification of sturgeon relying on the scute structure. The outcomes of this trial showed the effectiveness of this approach and highlighted the promising prospects of utilizing AI for species sex determination.

### **3.5 Promoting growth rates**

Different types of fish have their preferred temperatures for growing well. By keeping the temperature just right, fish farmers can help their fish grow faster and bigger [84]. But if the temperature goes too high or too low, it can slow down how fast the fish grows. In the world of fish farming, how quickly the fish grows is super important. This is where things get interesting with technology like AI. AI can help keep track of how fast these creatures are growing. By using AI, farmers can make sure everything is perfect for the fish to grow well, leading to better production. Nowadays, fancy gadgets are being used to keep a close eye on fish and shrimp. These devices use special observations to check their size, shape, where they are, and what they are doing [85]. Some studies showed that the water quality (WQ) can be checked in 3D in cages and large tanks using self-driving vehicles that move sensors up and down to create detailed 3D profiles [86]. It has been noted that indoor aquaculture systems and underwater net-pen setups are more stable. AI comes into play by building models that can predict how fast aquatic creatures will grow [87]. These models consider various factors like water temperature, oxygen levels, and food availability to estimate growth rates accurately [88]. This helps farmers cut waste and make their production smoother. By looking at a fish species' growth rate, water temperature, and other conditions, a predictive model can suggest the best feeding rate [89]. These models can also forecast harvest yields and dates, boosting efficiency and preventing diseases. Early signs of stress or diseases in aquatic life can be caught through these models, allowing farmers to act early and reduce harm to production [90]. Predictive modeling is great for farmers aiming to maximize output while being eco-friendly, as it can improve growth rates, efficiency, and sustainability in aquaculture. In a separate study focusing on optimizing feeding for salmon, AI was used to create personalized feeding plans based on each fish's traits, leading to better growth rates and feed use. Tailored feeding schedules can fulfill each fish's unique nutrition needs and boost growth rates by analyzing feeding habits and growth patterns [91].

### **3.6 Reproduction**

Understanding how organisms reproduce is vital, whether it is humans, animals, or plants, each having their unique ways of reproducing. In aquatic animals, temperature is a key to successful spawning, with each species needing specific temperature ranges. Fish farmers can boost reproduction by adjusting temperature conditions, leading to more fish on their farms [52]. Aquaculture, whether in freshwater or salt-water, uses various methods like tank systems, net pens, and integrated multi-trophic setups. AI is making waves in aquaculture, improving feeding, water quality, population control, and disease prevention [92]. Research on reproduction in aquaculture can help design better breeding plans, enhancing the health and output of farmed fish populations. Studies are also investigating the use of AI to manage fish reproduction. For instance, a study created a model to pinpoint ideal conditions for striped bass egg production. AI's potential in aquaculture is huge, promising better industry efficiency and sustainability. By optimizing fish reproduction, feeding, and growth through AI [93], fish health and productivity can improve, benefiting fish farmers' bottom line [94]. One crucial area of AI is computer vision technology, which can detect and judge things in place of the human eye and brain. Digital cameras are employed in 2D and 3D vision systems to gather data, which is subsequently sent to a computer for semantic analysis and decision-making [95]. According to this viewpoint, computer vision and image processing technologies are crucial for fish detection [96]. Fish species may be identified, counts can be estimated, and fish behavior can be understood using the detection findings from computer vision models. However, there are numerous obstacles to overcome in computer vision modeling for fish recognition, including fluctuations in illumination, low contrast, high noise, fish deformation, frequent occlusion, and dynamic background [97]. Nonetheless, within the last 10 years, the field of fish detection has advanced remarkably [98]. On the other hand, stereo vision technology makes it possible to precisely capture fish phenotypic and track the movement of free-swimming fish in three-dimensional (3D) coordinate systems. Stereo vision has become a key tool for building intelligent aquaculture models and gathering data as a result of the trend toward automation, intelligence, and accuracy in aquaculture management. In order to measure fish underwater, Harvey and Shortis [99] created an early stereo-video system with manual image processing software. Many deep learning-based models for stereo vision have since been created. Frequently, these models have a "multi-stage" pattern. Traditional tasks like fish detection, key-point detection, instance segmentation, and tracking can be improved by utilizing the 3D perception capacity of stereo vision technology and extracting fish attributes from individual RGB photos. These models can offer a more precise and clever solution for behavior analysis [100, 101], biomass estimation [102, 103], and fish size measurement [104]. Studies are also trying to use more advanced methods to take advantage of the deep characteristics offered by stereo vision, such as radiation-based 3D reconstruction algorithms [105] and 3D human pose recognition networks [104].

### **3.7 Breeding programs**

AI can develop predictive models of fish performance, by examining genomic data, aiding in more precise breeding programs focused on qualities such as disease resistance and growth rate. AI systems analyze extensive genomic data to identify genetic differences linked to specific traits, using this information to forecast fish

performance [106]. These models can forecast the performance of diverse fish populations under changing environmental circumstances and identify prime candidates for breeding to achieve particular objectives such as disease resistance or growth rate. Employing AI optimizes breeding endeavors, rendering them more focused and effective, thereby conserving time and resources while attaining desired traits. Augmenting the productivity and sustainability of fish populations through this method can yield substantial advantages for aquaculture and fisheries management. Consequently, the fusion of AI with breeding initiatives presents significant potential for propelling aquaculture and fisheries management forward, while also bolstering the genetic caliber and performance of fish populations [44].

### **3.8 Sustainability, efficiency, and behavior**

Aquaculture could provide a sustainable source of food, but it must be managed carefully to protect the environment [107, 108]. AI technology can help monitor important factors like water quality, fertilizer use, waste management, and overall productivity. Using AI in aquaculture can increase efficiency, support sustainability, reduce diseases, and enhance growth rates, making it a more reliable food source [44]. Temperature affects fish behavior; for instance, warmer waters can make species like tilapia and largemouth bass more aggressive, likely due to changes in metabolism and feeding habits. This area of fish behavior research is quite intriguing, especially with species like bluegills showing increased aggression in warmer conditions as they compete for food and space [109]. In the same way, Atlantic salmon was observed to get more aggressive in warmer environments, leading to higher stress levels and a greater chance of getting sick, which could affect how healthy and productive they are [110]. On the other hand, cold-water fish like yellow perch have been noticed to become more aggressive in warmer weather [110]. This behavior change might also affect how they eat and could result in more competition for limited resources. The impact of increasing temperatures on fish aggression can vary depending on the species and specific environmental conditions. However, it is commonly accepted that changes in water temperature can have a significant effect on how fish behave and their overall health and wellness. Some fish species become less active in colder climates due to their slower metabolisms and the need to save energy to stay warm, including a few that slow down in cooler weather [111]. Trout, which are cold-water fish, tend to become less active as the temperature decreases. To conserve energy, they often move to warmer areas, such as near the water's surface or close to the warmer flow from a tributary. Similarly, catfish are another type of fish that slows down in cooler weather. They prefer the deeper parts of the water where the temperature is more stable, allowing them to save energy [112]. Carp, freshwater fish that can tolerate a range of temperatures, also become less active in colder weather. They tend to move to deeper parts of the water to preserve energy. Pike, predatory fish, also slow down in cooler temperatures. They typically migrate to warmer, deeper waters to conserve energy. Additionally, walleye, a popular sport fish, become less active in colder weather and will seek out warmer areas, like near a warm tributary's outflow, to save energy [113].

### **3.9 Conservation genetics**

AI can play a crucial role in analyzing the genetic makeup of endangered fish species, offering deeper insights into their genetic diversity and how best to safeguard them. Safeguarding these fish is essential for the well-being of our ecosystems and for

preserving biodiversity. Endangered fish species confront various threats, including overfishing, habitat loss, pollution, and the impacts of climate change. Conservation genetics serves as a valuable tool in addressing these challenges by providing critical knowledge. By harnessing AI to delve into genetic data, scientists can pinpoint distinct populations within a species and unravel genetic variances both within these groups and across them. This knowledge can inform more targeted conservation strategies, like concentrating efforts on regions with rich genetic diversity or giving precedence to safeguarding vulnerable populations [114]. AI aids researchers in identifying genetic markers linked to crucial traits such as disease resilience or successful reproduction, pivotal for the survival and breeding success of fish species. Armed with this information, scientists can devise breeding plans that emphasize the preservation of these essential traits, thus bolstering the long-term viability of these species [115]. The integration of AI into conservation genetics facilitates a deeper comprehension of and protection for endangered fish species, which are fundamental for the health of aquatic environments and the communities dependent on them. Conservation genetics concentrates on safeguarding the genetic richness of imperiled species, with AI proving to be a valuable asset in this domain. It enables researchers to analyze vast genetic datasets more efficiently and accurately than conventional methods. By leveraging AI to scrutinize this data, researchers can unearth patterns of genetic diversity, such as distinctive or rare genetic traits. This understanding can guide effective conservation measures, like tailored breeding initiatives or the establishment of protected habitats [116].

Furthermore, AI can aid in pinpointing potential threats to the genetic diversity of endangered species including invasive species or habitat degradation. Early detection of these risks empowers conservationists to take proactive measures to mitigate their impact and shield vulnerable species. Overall, AI enriches our comprehension of endangered species and reinforces their prospects for long-term survival [117]. Moreover, AI holds the potential to revolutionize fish genome research, driving progress in aquaculture, fisheries management, and environmental conservation [118]. Nevertheless, ethical considerations surrounding the use of AI-powered genetic tools underscore the importance of employing responsible and sustainable practices. Thoughtful evaluation of the benefits and risks of AI in fish genome analysis is crucial to ensure that its application serves the interests of both humanity and the environment [44].

### **3.10 Genome editing and sequencing**

Through the analysis of fish genomes and genetic variations, researchers can pinpoint desirable traits such as disease resistance, rapid growth, and adaptability to diverse environments [119]. Leveraging AI, researchers can expedite and enhance the selection of optimal fish for breeding, surpassing traditional methods in speed and accuracy. This advancement holds the potential to elevate the efficiency and sustainability of aquaculture operations [120]. By learning from vast datasets, AI can identify genetic variations and understand how specific genes function. This is particularly useful in aquaculture, where AI can help spot desirable genetic traits and select the best candidates for breeding. Additionally, AI can monitor fish populations by examining genetic diversity and identifying markers that track fish movements and changes in populations [121]. AI can also contribute to creating new genetic tools, such as gene editing technologies, that improve the health and productivity of fish. Overall, AI has the potential to make significant advancements in fish genome

research, resulting in important breakthroughs in aquaculture management, including applications in genome editing and sequencing [122]. Analyzing large amounts of genetic information using AI can help speed up and make genome sequencing more precise. This is crucial for understanding the genetic characteristics of fish species [123]. AI algorithms assist scientists in pinpointing important parts of the genome and creating top-notch genome sequences by handling huge amounts of genetic data. This is a big plus for breeding and selecting fish in aquaculture. Researchers can pinpoint traits such as disease resistance, rapid growth, and adaptability in fish groups by scrutinizing their genomes for genetic distinctions. Through the integration of AI, researchers can expedite and enhance the selection of optimal breeding fish, surpassing traditional approaches in speed and accuracy [124]. This advancement holds the potential to enhance the efficiency and sustainability of aquaculture operations. AI and genome sequencing offer significant promise for advancing fish genome exploration and refining aquaculture methodologies. To augment fish genomes effectively for traits like heightened growth and disease resistance, AI can aid in refining genome editing technologies like CRISPR-Cas9 [125]. Genome editing techniques, including CRISPR-Cas9, hold the potential for bolstering traits in fish species, such as disease resilience and growth [126]. Nonetheless, perfecting genome editing methods can be laborious and resource-intensive. AI can expedite this process by pinpointing optimal genome editing locations and fine-tuning the CRISPR-Cas9 system for maximum efficiency and precision [127].

#### **4. Conclusion and future prospective**

In conclusion, the integration of Artificial Intelligence (AI) in aquaculture greenhouse systems marks a significant step toward revolutionizing the industry, enhancing productivity, sustainability, and overall efficiency. The transformative potential of AI in aquaculture is vast, offering a range of applications that can address critical challenges faced by traditional aquaculture practices. By leveraging machine learning algorithms, data analytics, and real-time monitoring, AI enables aquaculture operators to make informed decisions, optimize resource utilization, and mitigate risks effectively. One of the key advantages of AI in aquaculture greenhouse development is its ability to enhance environmental monitoring. Through the use of sensors, cameras, and monitoring devices, AI algorithms can collect and analyze data on key environmental parameters such as water quality, temperature, and nutrient availability. This data-driven approach allows operators to maintain optimal conditions for aquatic species, leading to improved growth rates, disease management, and overall productivity. By applying sensors, cameras, and monitoring tools, AI algorithms can gather and assess data concerning vital environmental factors like water quality, temperature, and nutrient levels. This data-centric method empowers operators to uphold ideal conditions for aquatic species, resulting in enhanced growth rates, disease control, and overall productivity levels. Furthermore, AI plays a crucial role in feed management within aquaculture systems. By analyzing data on feeding patterns, nutrient requirements, and fish behavior, AI algorithms can optimize feeding schedules, reduce waste, and ensure that aquatic species receive the necessary nutrients for healthy growth. This level of precision in feed management not only improves production efficiency but also minimizes environmental impact by reducing excess feed and nutrient runoff. Disease detection is another area where AI demonstrates its potential in aquaculture greenhouse systems. By monitoring changes

in animal behavior, vital signs, and environmental conditions, AI can detect early signs of disease outbreaks and alert operators to take preventive measures promptly. This proactive approach to disease management can significantly reduce the impact of diseases on aquaculture operations, safeguarding the health and well-being of aquatic species. Predictive analytics enabled by AI technology offers aquaculture operators valuable insights into future outcomes and potential challenges. By analyzing historical data, environmental trends, and system performance, AI algorithms can predict production outcomes, optimize resource allocation, and identify areas for improvement. This data-driven decision-making process empowers operators to plan effectively, mitigate risks, and optimize production outcomes in aquaculture greenhouse systems. Moreover, the ethical considerations surrounding the use of AI in aquaculture are crucial. As AI technologies continue to advance, it is essential to ensure that they are deployed responsibly, ethically, and in alignment with the well-being of aquatic species and the environment. Transparency, accountability, and data privacy should be prioritized to build trust and confidence in AI-driven aquaculture practices. In the future, the full potential of AI in aquaculture greenhouse development can be unlocked through continued research, innovation, and collaboration across the industry. By embracing AI technologies, aquaculture operators can enhance production efficiency, reduce environmental impact, and ensure the sustainability of aquaculture practices for future generations. Overall, AI represents a powerful tool for transforming aquaculture greenhouse systems, offering a pathway toward increased productivity, improved sustainability, and enhanced environmental stewardship. As the aquaculture industry continues to evolve, the integration of AI will play a pivotal role in shaping the future of aquaculture practices, ensuring food security, and meeting the growing demands of the global population. By unlocking the potential of AI in aquaculture, we can pave the way for a more efficient, sustainable, and resilient aquaculture industry that benefits both producers and consumers alike.

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## **Conflict of interest**

The authors declare no conflict of interest.

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Section 3

Environmental Control  
and Optimization

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## Chapter 4

# Humidity Optimization in Greenhouses

*Ioannis Lycoskoufis*

### Abstract

Greenhouse humidity control is essential for the successful cultivation of plants. This chapter consists of four parts. The first part includes an introduction and definitions of humidity. The second part distinguishes the sources and sinks of water vapour in the greenhouse through the water vapour balance, and describes the variations of humidity in the greenhouse. In the third part, the effects of humidity on plant growth and yield, physiological disorders and the susceptibility of plants to pathogen attacks are analysed. In the last part, methods of controlling high humidity in the greenhouse are developed. Control of high humidity in greenhouses can be achieved through natural ventilation, forced ventilation with heat exchangers, forced ventilation, high-temperature maintenance, condensation on a cold surface using cooling systems and absorption/adsorption by a hygroscopic material such as different types of desiccants.

**Keywords:** water vapour, transpiration, condensation, ventilation, dehumidification

## 1. Introduction

The greenhouse is a medium used for the growth and production of plants, so research in the greenhouse has the main objective of improving (technically and economically) the environment it creates in order to achieve the most efficient growth and production of plants.

One of the key factors in the composition of the plant's environment is the humidity contained in the atmospheric air. Optimal plant production depends on a specific humidity range. Relative humidity affects the water status of greenhouse crops and thus all processes related to transpiration, such as water balance, leaf cooling and ion transport. A major problem of the greenhouse climate is very high-relative humidity values, especially during the night. Research has shown that very high levels of humidity drastically reduce crop transpiration causing physiological disorders to occur, favouring the development of fungal diseases with the ultimate result of reducing the production of crops in the greenhouse. However, research on effective and economical methods of reducing humidity in the greenhouse is not significant.

### 1.1 Moisture definitions

Before discussing the effects of humidity on greenhouse crops, it should be noted that the amount of water vapour in the air can be expressed in different ways. *Absolute*

*humidity* is the amount of water vapour contained per unit volume ( $\text{g m}^{-3}$ ) or weight of air ( $\text{g kg}^{-1}$ ). The absolute humidity of air when expressed per unit volume of air is also called *water vapour density*, and when expressed per unit weight of air is also called *specific humidity*. *Relative humidity* is defined as the ratio of the actual partial pressure of water vapour to the partial pressure of water vapour in saturated air at the same temperature. The relative humidity is expressed in per cent. The relative humidity is 0 for dry air and 100% for saturated air. *Water vapour pressure deficit* is the difference between the absolute humidity of the air and the amount of water vapour that the air would have if it were saturated at the same temperature and pressure. The water vapour saturation deficit therefore expresses the amount of water vapour that the air of a given temperature and pressure can still absorb. The vapour pressure deficit can also be defined as the difference between the actual partial pressure of the water vapour and the partial pressure of the water vapour at saturation. The unit water vapour pressures are gaining acceptance by researchers. Grange and Hand [1] have reported that the vapour pressure deficit is probably the most useful term to describe the humidity of the air inside the greenhouse.

## 2. Humidity in greenhouses

### 2.1 Humidity fluctuations

Humidity is one of the determinants of the greenhouse's air environment. It usually tends to be high due to the evapotranspiration of the crop. Humidity and energy in the greenhouse are interrelated. Humidity exchanges in the greenhouse are combined with heat transfer by evaporation and condensation of water, taking and giving heat respectively in the form of latent heat. In addition, the temperature and air movement in the greenhouse, and therefore, the radiation and convection that cause them, greatly influence the physical processes and states of water. Radiation, by increasing the temperature created on the surface of the plant leaves, also regulates the rate of transpiration.

The water vapour density in the greenhouse is higher during the day, because the evaporation rate is higher than at night, but the relative humidity is lower during the day, because the air temperature is higher and ventilation is usually working. In a greenhouse, when equilibrium has been reached, the absolute humidity is approximately the same throughout the whole greenhouse space, but the temperature in the different parts of the greenhouse space is not uniform (e.g. near the cover is usually lower), so the relative humidity of the air is usually not the same in all parts of the greenhouse space. Therefore, the humidity problem is partly due to the uneven temperature distribution in the greenhouse, where locally high relative humidity is associated with locally low temperatures. The problem of very high relative humidity in the greenhouse usually occurs at night. During the night, the air cools down, so the relative humidity increases, and because there is no significant ventilation (the windows are closed at night), the relative humidity in the greenhouse area increases continuously. High humidity conditions are a condition that is typical of closed greenhouses in average night weather conditions [2].

The level of humidity in the greenhouse is determined by the balance between the sources and losses of water vapour in the greenhouse environment. The main source of water vapour in the greenhouse is the transpiration of the crop [3]. Crop transpiration rate is influenced by incident solar radiation,  $\text{CO}_2$  concentration,

temperature and relative humidity in the greenhouse. The humidity in the greenhouse is also increased by the evaporation of water from greenhouse surfaces, such as the soil surface. The humidity in the greenhouse environment is always higher than that of the outside environment due to evapotranspiration. Leaks of internal air into the external environment and the operation of the greenhouse ventilation (natural or mechanical) remove air with a high moisture content and replace it with external air with a lower moisture content. In this way, water vapour is lost from the greenhouse, so that ventilation causes a reduction in humidity in the greenhouse.

The phenomenon of surface condensation of water vapour is very often observed in areas with increased relative humidity, such as the greenhouse. The closer the dew point temperature is to the ambient air temperature, the higher the relative humidity and the greater the chance (with a slight decrease in ambient temperature or increase in ambient humidity) that the air will saturate and condense the water vapour it contains. Condensation begins to occur on greenhouse surfaces whose temperature is lower than the dew point temperature of the air. The frame construction elements and the cover obtain at night, more rapidly than all other surfaces, a lower temperature than that of the air in the greenhouse because of their direct contact with the cooler outside air. The surface of plants also cools very quickly at night because they lose heat through long-wavelength radiation. In some cases at night, especially in polyethylene-covered greenhouses, when the sky is clear of clouds, plants cool faster than air and water vapour condenses on them. Thus, condensation of water vapour on cold surfaces inside the greenhouse, such as the cover, removes humidity from greenhouse air. This may be desirable in glass greenhouses because the condensation of water vapour is in the form of a membrane and the condensate flows towards the perimeter of the greenhouse without the risk of falling on the plants. However, in polyethylene-covered greenhouses, the condensation takes the form of droplets, which do not spread across the cover and do not flow to the edge, but accumulate continuously and, as their weight increases or as the wind blows, fall on the plants in the form of rain and make them susceptible to attack by fungal diseases. Thus, a reduction in the relative humidity in the greenhouse can also occur through the forced movement of air by fans within the greenhouse, because this greatly increases the condensation of water vapour on the cold surface of the cover. However, this also increases the energy losses of the greenhouse due to increased convection, resulting in increased greenhouse heating costs. In addition, water vapour condensing on the inner surface of the cover releases its latent heat and increases the energy losses of the greenhouse. Many heated greenhouses, in order to reduce heating costs, have improved their insulation by installing a double cover. In this case, the condensation of water vapour on the inner surface of the cover is limited and thus, it is not possible to reduce the relative humidity in the greenhouse air. Thus, greenhouses with improved insulation have a more pronounced problem of high humidity inside compared to greenhouses with a single cover.

The unevenness in the temperature distribution in the greenhouse causes not only different transpiration of plants at different locations but also different frequency of water vapour condensation on the plants. Therefore, to avoid condensation, the dew point temperature should be well below that of the air. This is achieved either by reducing the water vapour content of the air or by increasing the temperature of the air and the construction surfaces, or by all of the above. When growing crops in the greenhouse are susceptible to fungal diseases, growers seek to keep their greenhouses not only at an appropriate temperature but also at a not too high level of humidity. To prevent locally high humidity, growers set the maximum relative humidity limit at a lower level than

that required for uniform conditions in the greenhouse. In addition, to limit the negative effects of very high humidity, growers are obliged to either increase the use of plant protection products or to dehumidify the air in their greenhouses. However, consumer demand for products free of chemical residues, which is becoming ever greater, is driving the search for plant- and energy-friendly methods to regulate high humidity levels. Therefore, during the cold hours there is a need to reduce the relative humidity in the greenhouse to maintain a suitable environment for healthy plant growth and production.

## 2.2 Greenhouse water vapour balance

The transpiration of the crop can be measured fairly accurately by the energy balance method. Initially, simple energy models used relationships linking external radiation to transpiration and later included energy from the heating system and plant growth [4]. More complex transpiration models are based on crop transpiration and leaf energy balance in which transpiration is characterized by canopy resistance [3, 5–7]. An accurate calculation of transpiration requires precise measurement or calculation of leaf temperature, leaf resistance (stomatal and surface), air resistance to water vapour diffusion and leaf area index.

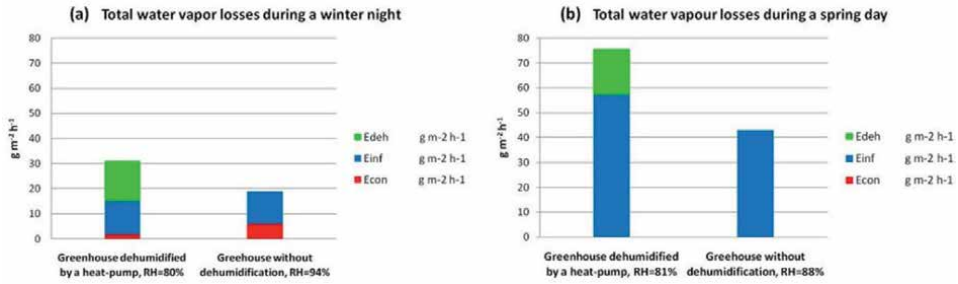
Most of the work, which has dealt with the study of greenhouse water vapour balance, has been carried out in hydroponically grown greenhouses. In these greenhouses, the greenhouse soil is isolated from the air environment by covering it, usually with polyethylene sheeting, and the crop is grown in plastic substrate bags. Thus, in these studies evaporation from the soil or from the holes in the bags is considered negligible [5, 6]. However, errors of up to 50% in calculated crop transpiration have been reported [8]. Boulard et al. [3] calculated evaporation from the holes of the substrate bags and found that this evaporation accounts for about 32% of the total evapotranspiration. In addition, they reported that the determination of transpiration, at night, by direct measurement of plant temperature was not as accurate ( $R^2 = 0.61$ ), and that an error of  $\pm 0.1^\circ\text{C}$  in the measurement of plant temperature causes an error in the determination of transpiration of  $2.5 \text{ W m}^{-2}$  at a time when the average total transpiration was estimated at  $10 \text{ W m}^{-2}$ . However, in most greenhouses the plants are still grown in the ground and no soil cover is applied. Thus, the contribution of evaporation from the soil to evapotranspiration is higher in these greenhouses compared to modern hydroponic greenhouses. Therefore, the determination of evapotranspiration by means of leaf temperature or the energy balance method becomes difficult and uncertain.

The humidity in the greenhouse air is due to crop evapotranspiration ( $E_{\text{ev}}$ ), that is, the sum of water vapour from the transpiration of the crop leaves ( $E_{\text{tr}}$ ) and evaporation from the greenhouse soil ( $E_{\text{s}}$ ):

$$E_{\text{ev}} = E_{\text{tr}} + E_{\text{s}} \left[ \text{g m}^{-2} \text{s}^{-1} \right] \quad (1)$$

Water removed from the greenhouse ground by evapotranspiration  $E_{\text{ev}}$ , when the windows are closed, mainly condenses on the greenhouse cover  $E_{\text{con}}$ , infiltrates into the outdoor environment  $E_{\text{inf}}$ , is removed by the dehumidification system  $E_{\text{deh}}$ , or changes the water vapour concentration in the greenhouse air  $dE$ :

$$E_{\text{ev}} = E_{\text{con}} + E_{\text{inf}} + E_{\text{deh}} + dE \left[ \text{g m}^{-2} \text{s}^{-1} \right] \quad (2)$$



**Figure 1.** Contribution of water vapour losses from a closed, unheated greenhouse under Greek conditions (Lycoskoufis, [9]).

In the case where no dehumidification method is applied in the greenhouse, then the  $E_{deh}$  parameter is zero (**Figure 1**).

The transpiration of the crop is calculated as a function of the net radiation ( $R_n$ ) available to the crop and the difference between the absolute humidity of the greenhouse air ( $x_a$ ) and the absolute humidity at saturation ( $x_a^*$ ) by the following relationship [5]:

$$E_{trans} = \frac{\frac{\epsilon r_b R_n}{\lambda} + 2LAI(x_a^* - x_a)}{(1 + \epsilon)r_b + r_s} \left[ g\ m^{-2}\ s^{-1} \right] \quad (3)$$

Where

$\epsilon$ : the ratio of the latent heat in the air to the heat sensible in the saturation.

$r_b$ : the resistance of the surface layer of the leaf.

$r_s$ : the resistance of the stomata of the leaf.

LAI: the leaf area index.

$\lambda$ : the latent heat of evaporation of water.

The condensation of water vapour in the greenhouse cover depends on the mass transfer conductivity ( $g_{con}$ ) and the difference between the absolute humidity at saturation at the cover temperature ( $x_c$ ) and the ambient absolute humidity ( $x_a$ ), and is calculated from the relationship:

$$E_{con} = g_{con} (x_c - x_a) \left[ g\ m^{-2}\ s^{-1} \right] \quad (4)$$

The mass transfer conductivity ( $g_{con}$ ) can be accurately calculated from the heat transfer coefficient  $h_{con}$ , by means of:

$$g_{con} = \frac{h_{con}}{\rho_a * C_p * Le} \left[ m\ s^{-1} \right] \quad (5)$$

where  $h_{con}$  is the convection heat transfer coefficient, in  $W\ m^{-2}\ ^\circ C^{-1}$ ,  $\rho_a$  is the air density in  $kg\ m^{-3}$ ,  $C_p$  is the specific heat of air, in  $J\ kg^{-1}\ ^\circ C^{-1}$ , and  $Le$  is the Lewis number, defined as follows:

$$Le = \left( \frac{\alpha}{D} \right)^{0,66} \quad (6)$$

where  $\alpha$  is the thermal diffusivity calculated at  $2216 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$  and  $D$  is the diffusion coefficient at  $2,5 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ . There are several studies that refer to the determination of the convection heat transfer coefficient on the inner side of the greenhouse cover as a function of the temperature difference between the cover ( $T_a$ ) and the greenhouse air ( $T_c$ ). Most relationships that have been proposed for determining the convection heat transfer coefficient ( $h_{con}$ ) are of the form:

$$h_{con} = \frac{A_c}{A_g} * c * (T_a - T_c)^{1/3} \text{ [W m}^{-2} \text{ K}^{-1}] \quad (7)$$

Where  $A_g$  is the greenhouse ground area, and  $A_c$  the greenhouse cover area.

Since the effect of the temperature difference between the cover and the air in the above relationship is relatively small [5], the value of the convection heat transfer coefficient ( $h_{con}$ ) can be considered as constant. Thus, Jolliet [6] states that, the value of the convection heat transfer coefficient can be considered equal to  $3.5 * A_c / A_g$ .

The water vapour losses to the outdoor environment depend on the conductivity of the infiltration and the difference between the absolute humidity of the outdoor air ( $x_o$ ) and the absolute humidity of the greenhouse air ( $x_a$ ) and are calculated from the relation:

$$E_{inf} = g_{inf} * (x_a - x_o) \text{ [g m}^{-2} \text{ s}^{-1}] \quad (8)$$

The infiltration conductivity  $g_{inf}$  is determined by the refresh rate of the greenhouse air  $q$  ( $\text{m}^3 \text{ s}^{-1}$ ) and the greenhouse area  $A_g$  as follows:

$$g_{inf} = \frac{q}{A_g} \text{ [m s}^{-1}] \quad (9)$$

The leakage ventilation rate  $q$  ( $\text{m}^3 \text{ s}^{-1}$ ) can be determined using a tracer gas such as  $\text{N}_2\text{O}$  [10].

### 3. Effects of relative humidity on crops

#### 3.1 Effects on photosynthetic capacity

Plants may exhibit an increased rate of photosynthesis with increasing humidity because whole-plant water uptake cannot always satisfy their transpiration at lower humidities. Acock et al. [11] measured net photosynthetic rates in tomato plants at various concentrations of carbon dioxide and at different humidity levels, their results showed that the photochemical capacity of the leaf at 0.5 kPa of saturation deficit was 18% greater than that at 1 kPa and at 400 ppm  $\text{CO}_2$ , but only 5% greater

at 1200 ppm CO<sub>2</sub>. Detailed analysis of the data showed that the transport of CO<sub>2</sub> is affected by the stomatal conductance which in turn is affected by humidity content. However, the data showed variation and the increase in photochemical capacity should be treated with caution. More recent research has reported that the photosynthetic capacity of plants is reduced at very high humidities due to lower carboxylase sufficiency [12]. Xu et al. [13] reported that at higher saturation deficits, plant photosynthetic capacity increases due to increased chlorophyll content of leaves, increased soluble protein content and higher Rubisco activity.

### 3.2 Physiological disorders

Calcium is an essential nutrient that is needed in relatively high amounts to maintain the structural integrity of cells and to regulate various metabolic processes. Mature plant leaves normally contain about 1–3% calcium per unit dry weight. The calcium-related disorders are numerous and varied, like blossom-end rot in tomato and pepper, and tip-burn in lettuce, in cabbage, in chrysanthemum. In addition, there are examples of calcium-related disorders for almost every fruit and vegetable. Symptoms of calcium deficiency are usually observed when the calcium content falls below 1% of dry weight in the respective susceptible tissue. Surprisingly, calcium deficiencies are often observed when there is no deficiency of the element either in the plant or in the rootstock. The essential problem is the inadequate distribution of calcium in the plant and this occurs because the movement of the element in the sensitive tissue is very slow and insufficient to meet the requirements [14]. It appears that, a large proportion of the amount of calcium absorbed by the fruit remains in the pedicel and calyx with very little movement to the tip of the fruit [14].

Many physiological and morphological disorders related to calcium levels in plant tissues are usually related to environmental conditions (relative humidity) or insufficient calcium supply to the roots [15]. However, the effect on plant growth as a water-related process and nutrient uptake has been analysed. Grange and Hand [1] reported that air humidity with a water vapour saturation deficit of 0.3 to 1 kPa has little effect on plant physiology. However, saturation deficits higher or lower than these values can often be found in greenhouses. In northern Europe, reduced greenhouse air exchange often results in an increase in humidity inside the greenhouses, leading to a reduction in transpiration. In contrast, in southern Europe, where greenhouses are characterized by high ventilation rates, higher temperatures in spring and summer are often accompanied by high vapour pressure deficits during midday [16]. High humidities promote physiological disorders due to reduced transpiration and therefore reduce nutrient uptake [17]. There are several reports linking the observed reduced calcium concentrations under elevated humidity conditions with negative symptoms in plant growth [18]. To maintain leaf elongation and to avoid any production losses under elevated humidity conditions due to Ca deficiency, at least 8.7 MJ m<sup>-2</sup> d<sup>-1</sup> of total solar energy is required [19]. However, the importance of transpiration in long-distance calcium transport is questioned [20]. Thus, Mulholland et al. [12, 21] and del Amor and Marcelis [15], conducting combined experiments with different humidity levels and different Ca concentrations in the nutrient solution, concluded that low leaf Ca contents were not responsible for the negative effects on plant growth under elevated humidity conditions. In extreme conditions of high solar radiation and high humidity, reduced transpiration can cause high leaf temperatures and thus damage to the leaves.

### **3.3 Effect on diseases**

Although biological control agents have been successfully applied in recent years for most insect pests of greenhouse crops, biological control of diseases is much less developed [3]. Recent research on the toxicological impact on greenhouse products has shown that disease management still relies heavily on fungicides. Most airborne fungal pathogens, especially botrytis, are considered one of the biggest problems for greenhouse crops.

Fungal diseases are among the most aggressive pathogens of greenhouse crops. Atmospheric humidity and water availability are particularly important for fungal diseases, because they need significant amounts of water for their spread and for the release of their spores. Most fungal pathogens need water around their spores to germinate. High atmospheric humidity inside the greenhouse often leads to humidity condensation on the leaves. In addition, at high humidity levels, when the temperature of the cover drops below the dew point results in water vapour condensation on the cover, the droplets that were formed on the cover can fall on the plants. These conditions are not uncommon in greenhouses and crop protection requires humidity reduction. However, humidity control is a limiting factor in these conservation practices and growers often adopt a risky management strategy, with frequent fungicide applications [22]. In practice, botrytis control in floriculture comes after climate control and is usually controlled with fungicides. Research has resulted in decision-system based (DSS) models [22–24]. These approaches used models of botrytis epidemiology from which decisions were made on various control measures. However, the focus of these decision-making systems was oriented towards a more direct application of fungicides, rather than an improvement in climate control strategies [25]. In addition, fungicide use is limited by the development of fungicide resistance in pathogens [26], the negative impact of fungicides on plant growth, visible residues on plant surfaces [26, 27] and environmental issues.

Protecting plants from disease through environmental control is becoming very important, as consumers want either food free from chemical fungicide residues or products in which no fungicides have been used at all. In addition, creating an atmosphere that is less conducive to disease will also reduce the selection pressure for pathogens to develop resistance to chemical fungicides. An aerial environment that prevents the rapid spread and establishment of a disease will help extend the useful commercial life of pesticide products.

Microclimate parameters have long been recognized as the most important factors in the spread of fungal diseases and greenhouse climate management for disease control. Greenhouse microclimate parameters such as air temperature, relative humidity, leaf temperature and the duration of humidity retention on the leaf affect the growth and development of crops, as well as the speed of spread of diseases caused by fungal pathogens such as botrytis. This means that, the control of the environment should be determined in such a way as to ensure good crop response and at the same time avoid conditions favourable to disease development. It is not easy to determine the desired humidity that should be present in the air of the greenhouse. It is also known that there is a great variability of relative humidity within the greenhouse, especially near the surface layer of the crops, that is the conditions that influence the behaviour of the crop and pathogens. Assuming that water vapour saturation deficit values between 0.3 and 1 kPa do not affect crop growth, the question remains what is the desired humidity level for botrytis control. It is accepted by the majority of researchers that botrytis infection and spread are favoured under high humidity conditions. Many different humidity values are reported in the literature as desirable. Nederhoff [28] suggested maintaining relative

humidity below 85% as a safe measure to avoid botrytis. Zhang et al. [29], in an unheated greenhouse, used a simple criterion: when relative humidity is above 90% there is water available on the plant surface. Korner and Challa [30] limited relative humidity to a maximum of 93% for a maximum of 48 consecutive hours.

### 3.3.1 *The botrytis*

Botrytis is a widespread pathogen that causes severe losses in fruit, vegetable, flower and pot plant crops, and particularly important in greenhouse crops. The pathogen attacks all above-ground plant parts: flowers, fruits, leaves and shoots. Usually, it does not attack green healthy tissues such as leaves and shoots, even under conditions of very high relative humidity, unless there are wounded or dead areas. Penetration occurs from wounds and from tissues with low resistance, such as flower petals [31, 32]. Symptoms include brown spots, mottling, wilting and necrosis of plant parts, with large numbers of spores growing on dead tissues. Sometimes symptoms appear after harvest, as a postharvest disease [33].

The risk and extent of infection depends on two factors: firstly on the number of fungal spores in the greenhouse and secondly on the environmental conditions [28]. In the greenhouse environment, botrytis conidia are always present [34] and when conditions are right some spores establish and multiply. In particular, wounded plants or old leaves in the greenhouse soil are a source for millions of botrytis spores. Boulard et al. [35], considering the concentration of fungal conidia as a particular physical quantity, tried to determine their origin in a young greenhouse rose cultivar, that is whether they originate from the external environment of the greenhouse or are produced inside the greenhouse. Their results showed that the origin of the infections was mainly internal, about 2/3 of the total amount of conidia. However, due to the external climate and greenhouse window openings, the origin can vary widely from one season to another, with the tendency to become increasingly internal as the crop grows.

Botrytis spores contain very little water and need to absorb water from the environment to germinate. This explains why the disease has been linked to very high relative humidity. The spores germinate well in free water, especially if the water contains nutrients (sugars). One of the main characteristics of the botrytis is its dependence for germination and infection on the duration of humidity on plant leaves. Condensation of water vapour on plant leaves provides a favourable environment for spore germination [36]. In addition, a minimal period of leaf wetting can stimulate growth and development even after fungal penetration. It has been reported that necrotic botrytis lesions occur on flower shoots and petals when relative humidity is higher than 95% [34]. The most favourable temperature range for infection is 10-20°C, but infections can occur even at 2°C and above 25°C [37, 38]. However, spores are susceptible to dehydration and die after long periods of low humidity conditions of 60% [28], but after short periods of dehydration (less than 2 hours) spores continue to germinate when the leaf surface is moistened again [28] and this effect is cumulative [39]. Spores form at very high relative humidity and temperatures of 15-25°C are ideal [28]; however, botrytis can also grow at lower or higher temperatures. Botrytis spores are released when the affected plant tissues are disturbed or when the relative humidity changes abruptly, for example in the morning or late afternoon. The spores are transmitted by air currents or remain intact on affected plants.

The infections of the shoots are different. Plant shoots can be infected either by invasion of the fungus from already infected stems and peduncles or by direct infection of wounds after pruning and harvesting [40]. Fresh wounds supply enough

humidity (plant juices) to the fungal spores to enable them to germinate. Further growth of the shoot infection is favoured by high relative humidity, because under conditions of high relative humidity it takes longer for wounds to dry [28]. Botrytis infection of the shoot can eventually envelop the shoot and kill the entire plant causing significant production losses [41, 42].

With the objectives of avoiding the encouragement of botrytis by controlling the environment, reducing the involvement of fungicides in greenhouses and reducing energy consumption by using low relative humidity levels, a model was developed to regulate the opening of windows of heated greenhouses based on the duration of humidity on the leaves [25].

### **3.4 Effects on plant growth**

Plant and crop growth can be affected by humidity if humidity affects either the leaf area ratio or the rate of net photosynthesis. Such effects can occur at excessive values of atmospheric humidity beyond the normal range (0.3–1 kPa) found in greenhouses. For example, very low humidities (vpd greater than 1 kPa) can cause leaf water stress when there is a delay between water uptake by roots and transpiration by leaves. Hoffman [43] reported that growth is negatively affected when the saturation deficit is greater than 1 kPa. There is little or no effect of humidity on growth at saturation deficits of 0.3–1 kPa [1]. Van de Sanden [44] found no significant effect of humidity in the range 0.3 to 1.2 kPa on the growth of cucumber seedlings.

Conversely, very high humidities can have devastating consequences for many crops, where the effects on growth often vary. For example, the dry weight of plants grown in a high humidity greenhouse was significantly reduced [45], but the opposite was observed when grown in a controlled chamber environment with similar humidities [11]. del Amor and Marcelis [15] using tomato plants in controlled environment chambers found that plants grown at high humidity (vpd 0.13 kPa) showed reduced total dry weight and reduced leaf area. Reduced leaf size was also observed by Holder and Cockshull [18] in tomato plants grown in the greenhouse at high humidity (vpd 0.15 kPa). Munholland et al. [21], in addition to a reduction in leaf size, reported a reduced number of leaves per tomato plant under high humidity conditions (vpd 0.1 kPa). Reduced total leaf area and reduced leaf dry weight in chrysanthemums under conditions of increased humidity (vpd 0.13 kPa) were reported in Ref. [46]. Bakker et al. [47] investigated the effects of different levels of humidity during the day and night in a cucumber crop. The levels of saturation deficit during the day ranged from 0.57 to 0.91 kPa and during the night from 0.26 to 0.66 kPa. Vegetative growth was increased by high humidity during day or night, but early production was not affected by the different humidity treatments. High humidity appears to affect the morphology of plants probably by altering their hormonal balance [48]. The effects are small unless the humidity is very high (saturation deficit less than 0.2 kPa) for most of the growing season (**Table 1**). The maintenance of high humidities has devastating effects on the growth of the aboveground part of tomato, causing reduced growth or necrosis of the crown, damage to the leaves and woodiness of the shoot [49, 50]. Bakker [48] reports similar damage to cucumber seedlings, with sporadic root formation on the shoot.

### **3.5 Effects on yield**

The reproductive growth of crops can be affected by humidity. In tomato, there is little but obvious direct effect of humidity on flower development, but significant

	Greenhouse	
	Controlled relative humidity Mean nighttime vpd = 0.265 kPa (0.216–0.424 kPa)	Uncontrolled relative humidity Mean nighttime vpd = 0.103 kPa (0.010–0.299 kPa)
Leaf number per plant	32a	25b
Mean leaf size (cm <sup>2</sup> )	837a	710b
Mean leaf area per plant (m <sup>2</sup> )	2.67a	1.77b
Fruit number per plant	12.6a	8.0b
Mean fruit weight (g)	408a	397a
Fruit yield per plant	5.2a	3.2b

**Table 1.**

*Cucumber growth and yield parameters as affected by the vapour pressure deficit (vpd) of the greenhouse air. Means within the same line followed by the same letter do not differ significantly based on LSD-test at  $\alpha = 0.05$ . (Lycoskoufis [9]).*

effects on pollination have been observed. Picken [51] concluded that pollination is only affected when humidity is outside the 0.2–1 kPa saturation deficit range. However, if humidity is too high, then pollen is less likely to be ejected from anthers and when the saturation deficit is greater than 1 kPa, then there is a risk that pollen will not stick to the stigma. Thus, Holder and Cockshull [18] reported that the taxa associated with smaller leaves (at high humidity levels) produced smaller fruits and therefore lower yields compared to the low humidity treatments (**Table 1**). Among other things, the relative humidity in the greenhouse also affects the quality of vegetables such as tomato [13, 18, 21] and cucumber [47, 52].

## 4. Methods of reducing humidity in the greenhouse

For the development of any greenhouse humidity reduction system, the rate of water vapour removal from the greenhouse must be determined to keep humidity levels within the desired limits. The desired rate of water vapour removal from the greenhouse can be determined by taking into account the processes that determine the equilibrium of the greenhouse water vapour. This requires a mathematical description of the interaction of crop evapotranspiration with the greenhouse microclimate, as well as the processes of water vapour condensation and ventilation, as presented earlier in this chapter.

Control of high humidity in greenhouses can be achieved through natural ventilation, forced ventilation with heat exchangers, forced ventilation, high-temperature maintenance, condensation on a cold surface using cooling systems and absorption/adsorption by a hygroscopic material such as different types of desiccants.

### 4.1 Dehumidification with ventilation

The usual practice, when there is very high relative humidity in the greenhouse, is to ventilate. In heated greenhouses, even in cold weather, when the relative humidity is too high in the greenhouse, it is necessary to open the windows slightly for a short period of time. This allows the humid air to escape and be replaced by the outside air which, due to the lower temperature, has a lower absolute humidity. When the

outside air is mixed with the warmer inside air, its water vapour capacity is increased and the relative humidity is reduced overall, even if an amount of heat is lost, but this is supplemented by the heating system. When ventilation is used for cooling the greenhouse, there is no additional energy consumption, but when heating is used, it is obvious that ventilation is an energy waste, since the high enthalpy internal air is constantly replaced by low enthalpy external air. Therefore, in the winter season and when heating is required, dehumidification by ventilation results in an increase in energy consumption.

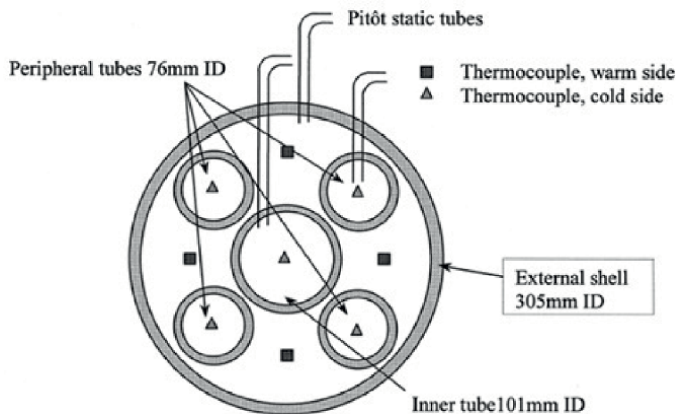
In modern greenhouses, environmental control systems have energy-saving functions with dynamic environmental control. In these practices, greenhouse ventilation is reduced to a minimum, resulting in high relative humidity levels (up to 100%) due to plant transpiration. This means that humidity control can counteract the energy savings from dynamic temperature regulation [30]. De Zwart [53] reported that controlling humidity by this method increases heating costs by 20%, De Halleux and Gauthier [54] reported that this increase ranges from 12.6 to 18.4% depending on the ventilation strategy followed, while Campen et al. [55] reported that sensible heat loss increases from 5 to 20.5% depending on the crop. Therefore, humidity control is a limiting factor of energy savings in the greenhouse. Kittas and Bartzanas [56] studying the effect of the type of window opening, on energy consumption, during greenhouse dehumidification with ventilation and simultaneous heating, concluded that greenhouses with rolled side window have lower energy consumption compared to greenhouses with side window opening with toothed arm.

Natural ventilation is a method of dehumidifying the greenhouse that is not sufficiently controlled. The operation of natural ventilation is influenced by the geometric characteristics of the windows and the surrounding area, the difference in temperature between the indoor and outdoor air, and the direction and speed of the wind, so its operation may vary in different greenhouses. The fact that this method is difficult to control results in the dehumidification carried out exceeding that required, with the direct consequence of increasing energy consumption. In addition, natural ventilation increases the heterogeneity of the greenhouse climate which can be the cause of humidity problems in the greenhouse.

#### **4.2 Dehumidification with a combination of forced ventilation and heat exchanger**

In order to save energy used during dehumidification, the use of forced ventilation in combination with a heat recovery unit has been studied. In this case, the warm indoor air leaves some of its heat to the incoming cold air to replace it. Thus, the temperature of the incoming air is at a temperature between that of the external and internal environment of the greenhouse. Albright and Behler [57] tested such a heat exchanger to control greenhouse humidity and concluded that about one-third of the enthalpy could be recovered from the ventilation air. De Halleux and Gauthier [54] simulated this system and concluded that the use of heat recovery exchangers could reduce energy consumption for dehumidification by 40–60%, depending on the ventilation mode (on-off or continuous adjustable supply). However, this energy saving did not justify the cost of this equipment. The typical efficiency of an air-to-air heat recovery exchanger is in the order of 40%.

In a more recent study, Rousse et al. [58] studied a heat recovery unit in Canada, which consisted of a multitube system inside another plastic tube (**Figure 2**). The outside cold air circulated in the pipes that made up the multitube, while the hot and



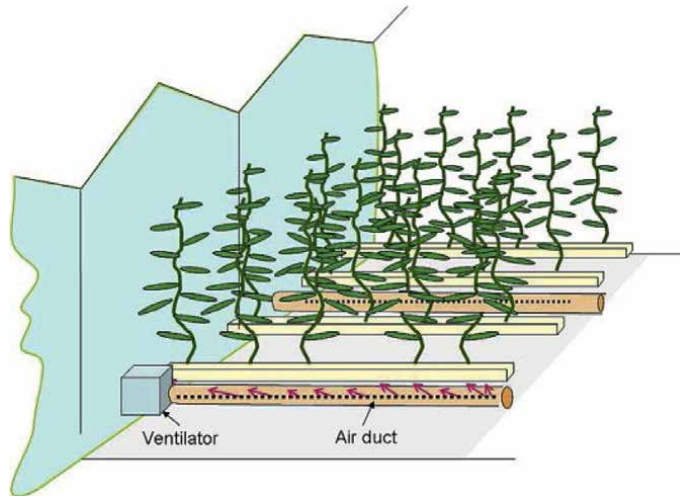
**Figure 2.** Schematic of the prototype cross section of the heat exchanger used for greenhouse dehumidification (Rousse et al. [58]).

humid greenhouse air circulated in the external pipe that enclosed the multitube. The total length of the heat exchanger was 24.3 m, and it was used to dehumidify a 220m<sup>2</sup> greenhouse. This unit had an efficiency of around 80%. A ventilation flow rate of 0.9 changes (of greenhouse air volume) per hour was not sufficient to dehumidify the greenhouse. The efficiency of the system was determined by the ratio of the recovered thermal power to the electric power consumed by the fan and ranged between 1.4 and 4.8 in this study.

Finally, Campen et al. [59] in an econometric approach reported that dehumidification of the greenhouse using a heat recovery unit compared to the classical dehumidification method reduces energy consumption for heating by 4.5–13%. Therefore, the systems studied for heat recovery either had low efficiency or were unable to reduce the relative humidity in the greenhouse and their installation costs did not justify the energy savings achieved. Air-to-air heat exchangers are an alternative controlled condensation mechanism, preferable in cold climates, while their efficiency decreases during summer or in mild climates.

### 4.3 Dehumidification with forced ventilation

Forced ventilation by fans offers more control over the ventilation rate, which is essential because “incomplete” ventilation can lead to low greenhouse VPD, while the excessive ventilation can increase energy consumption for heating. Both high-tech and low-tech modern greenhouses to reduce heat loss are equipped with thermal screens, which can be opened over the plants during nighttime. In this case, the greenhouse air under the cover, on the greenhouse roof, reaches a lower temperature and absolute humidity compared to the air under the screen around plants. This reduces both air leakages to the outside and the condensation of water vapour on the inner surface of the cover, resulting in a high level of RH in the greenhouse. When the humidity under the thermal screens exceeds a certain threshold, the screens are opened slightly to allow the air above and below the screen to mix more easily and control the high RH. This method successfully reduces high RH in the greenhouse but is not very accurate because the control operates over a small range of openings. Furthermore, this method has negative effects on crop growth due to the horizontal



**Figure 3.** Schematic diagram of the system where the ventilator is located at the sidewall of the greenhouse drawing in outside air and distributing it via ducts [55].

temperature differences caused by the large distance between the small screen openings. Campen et al. [55] described the design process and the testing of an alternative system for the humidity control had been developed by blowing of dry air under the thermal screen (**Figure 3**). Their calculations showed that the system required a maximum capacity of  $6\text{m}^3\text{h}^{-1}\text{m}^{-2}$  when outside air was used to maintain the relative humidity within given limits. When this system is used, the climate under the thermal screen is more homogenous with average temperature differences on a daily base being less than  $1^\circ\text{K}$ . They concluded that this system is easily controllable and increased the ventilation efficiency of the greenhouse. Therefore, the humidity set points could be adjusted more strictly, thereby saving energy [55].

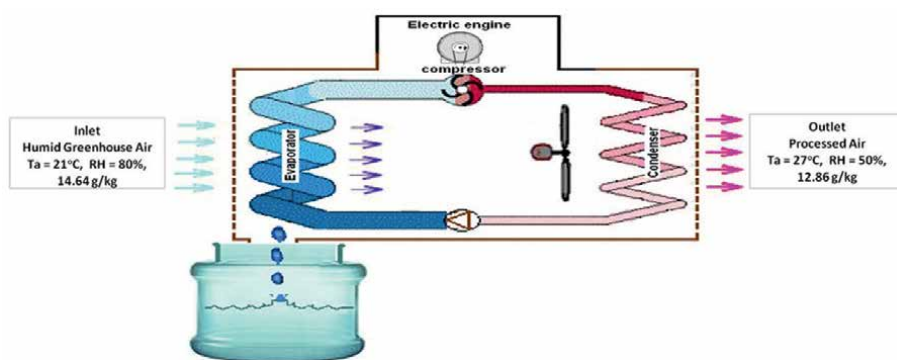
There are three more alternative methods of removing humidity from the air: a. by cooling the air to a temperature below the dew point to induce water vapour condensation, b. by the interaction of the air with a hygroscopic material, which absorbs or adsorbs humidity from the air due to the partial vapour pressure difference, or c. by increasing the air pressure to induce water vapour condensation at the given room temperature. The method of increasing the air pressure to cause condensation of water vapour is used in analytical, scientific devices, but its application to dehumidify greenhouse air is considered uneconomical. Therefore, the methods of active humidity reduction that can be used in the greenhouse are based either on reducing the humidity of the air by cooling it below the dew point or on hygroscopic absorption. These methods remove excess humidity from the greenhouse air by converting the latent heat of water vapour into sensible heat.

#### 4.4 Dehumidification by air cooling and condensation on a cold surface

When air comes into contact with a surface with a temperature below the dew point, its excess absolute humidity condenses on that surface, so the air is dehumidified. The amount of humidity that is removed depends on the difference between the absolute humidity of the air in the greenhouse and the absolute humidity at the dew point, which, it should be noted, must not be less than  $0^\circ\text{C}$ , so that condensation

takes place in liquid form. The most common method of dehumidification is the use of refrigerated exchangers. This method typically involves an exchanger in an air stream with a refrigerant recirculated into the exchanger at a temperature below the dew point of the air. The amount of humidity removed depends on the temperature and humidity of the air, the temperature of the exchanger, and the mass flow rate of the passing air. Commonly used cooling media include ice water and glycol solutions. When the heat exchanger is the evaporator of a heat pump, then its temperature is determined by the refrigerant fluid (**Figure 4**). Because the temperature of the exchanger is below the dew point of the air, humidity condenses on it, and is collected in a container and removed. This water can be reused.

Typically, dehumidification of air through cooling below the dew point is carried out by conventional vapour compression systems. Many researchers have used an air-air heat pump for greenhouse dehumidification, where the greenhouse humid air was first passed through the pump evaporator, cooled and left some of its humidity and then pumped through the pump condenser to the greenhouse at a higher temperature [3, 60, 61]. Chasseriaux [60] attempted to dehumidify a double-cover polyethylene greenhouse producing dripping roses with an area of 3000m<sup>2</sup> using a 2.8 kW electric heat pump. This heat pump could remove about 5 litres of water per hour. However, this was not sufficient to improve the greenhouse environment in terms of humidity. Similarly, the greenhouse environment was not significantly affected by a similar heat pump (2 kW) used in a greenhouse 7.5 times smaller than the first one (400 m<sup>2</sup>) during the night [3]. However, in this case water vapour condensation in the cover was reduced. Han et al. [62] compared dehumidification options using four heat pump dehumidifiers with total power of 7.2 kW, an air-to-air heat exchanger and an exhaust fan system in a commercial tomato greenhouse, 267m<sup>2</sup> in Canada and showed that the heat pump system had the lowest overall energy consumption. In another study, Arbel et al. [63] tested a Combined Heating and Dehumidification (CHD), which is based on a refrigeration cycle for drying the air, and a heat exchanger for heating. Their results indicate that the CHD prototype capability of energy saving of about 80% in comparison to without thermal screen and with ventilation greenhouse operation mode and 60% in comparison to thermal screen and with ventilation greenhouse operation mode. In regions with a mild climate, such as the Mediterranean region, to maintain the relative humidity using an air-to-air heat pump up to 80%, the maximum energy consumption during winter reaches 10.9 W m<sup>-2</sup>, while during spring it reaches 12.3 W m<sup>-2</sup> [61]. In these areas, when the minimum air temperature exceeds the



**Figure 4.**  
*Schematic of the operating principle of the dehumidifying heat pump.*

minimum favourable temperature for plants, dehumidification can only be carried out by natural ventilation, without energy consumption. Since this method is applied during periods when heating is required, the absorbed energy (sensible and latent) from the heat pump evaporator is delivered through the pump condenser to the greenhouse air, reducing the consumption of the heating system (if installed). In greenhouses, which do not have heating systems, this energy released leads to an increase in the temperature of the air inside the greenhouse, thus improving the environment for the crops. Therefore, when dehumidifying a heated greenhouse with a heat pump system, no additional energy is consumed to operate the system since the energy consumed by the heat pump is deducted from the consumption of the heating system. Therefore, for the decision to introduce a dehumidifying heat pump into the climate control mechanisms of the greenhouse the only criterion is the purchase cost of the heat pump. The purchase cost of an air-to-air heat pump is determined by its size, and Campen et al. [59] reported that the cost of a heat pump was estimated at 0.50 €/W.

Campen and Bot [64] presented a system for removing humidity from greenhouse air based on condensation of water vapour on cold-finned metal ducts cooled by low-temperature water at about 5°C (**Figure 5**). The pipes ran the entire length of the greenhouse and were located near the bottom of the gutter, and the greenhouse air passively came into contact with the cooled pipes, cooled and released some of its humidity. In the greenhouse, the desired temperature was set at 20.5°C and the system operated when the air humidity deficit was less than 4 g kg<sup>-1</sup> (i.e. 75%). To achieve temperature uniformity along the finned ducts, the water flow inside them was high (8 m<sup>3</sup> h<sup>-1</sup>). However, it was not possible to maintain the relative humidity inside the greenhouse at the desired level, reaching 90%. The above system at a greenhouse air temperature of 20.5°C and relative humidity of 90% could remove 36 g m<sup>-2</sup> h<sup>-1</sup>. The study of the system showed that the ratio of removed latent heat to total removed energy was less than 50%, depending on the relative humidity inside the greenhouse; thus, the total removed energy from greenhouse was more than twice the energy required for dehumidification. By using a heat pump, the latent and sensible heat collected on the cold surface could be returned to the greenhouse along with the power required to operate the heat pump, but in this study the possibility of heat recovery was not studied. The installation of this system caused a reduction in the light intensity in the greenhouse of 3%. Gao et al. [65] studied this system and compared it with the dynamic ventilation method and the heat recovery ventilation method, they



**Figure 5.** Photograph of the greenhouse where finned tubes are placed under the gutter and an enlargement of a finned tube with condensation on the surface Campen and Bot [64].

finally concluded that the dehumidification method with cooled finned ducts was less competitive than the other methods mainly due to higher energy costs.

#### **4.5 High-temperature maintenance**

In hot climates, during the day, maintaining a higher temperature to control humidity cannot be applied because plants will be exposed to heat stress. During the night, the RH inside the greenhouse tends to increase due to lower temperatures in the greenhouse. As the greenhouse gets colder at night, RH increases and can reach saturation levels, resulting in condensation on the greenhouse cover and plants. Maintaining a high temperature inside a greenhouse at night can be an effective method for reducing RH because this raises the pressure differential between internal and external air in the greenhouse, thus increasing air and water vapour leakage to the external environment. In addition, the temperature difference between the air and the greenhouse cover is increased, and this increases the condensation of water vapour on the cover and reduces the relative humidity in the greenhouse. However, to maintain a higher temperature in the greenhouse during the night, supplementary heating is required a practice that increases the cost of heating greenhouses.

#### **4.6 Dehumidification with hygroscopic absorption/adsorption**

An alternative method of reducing the humidity of the air is to absorb/adsorb the humidity from a solid or liquid hygroscopic material. Hygroscopics are materials that have a high affinity for water vapour [66]. Research on the application of hygroscopic greenhouse dehumidification is scarce [59]. Seginer and Kantz [2], calculating the water vapour balance for a single- or double-cover greenhouse, concluded that in average weather conditions hygroscopic dehumidifiers have an energy advantage over simultaneous heating and ventilation in well-insulated greenhouses. Campen et al. [59] used a simulation model comparing different methods of greenhouse air dehumidification concluded that hygroscopic dehumidification has the advantage that latent heat is directly converted into sensible heat and can be used to heat the greenhouse. Although there are several experimental studies on dehumidification of buildings using hygroscopic materials [67–69], experimental tests on dehumidification of greenhouses using hygroscopic materials have only appeared in recent years [70, 71]. The removal of humidity from the air depends on the difference in vapour pressure between the hygroscopic and the air. Absorption always releases heat which includes the latent heat of the absorbed water vapour from the dehumidifier and an additional heat of absorption ranging between 5 and 25% of the latent heat [66], and this additional heat is also called the differential enthalpy of dissolution [72]. This heat is transferred to the hygroscopic material and to the air. The process of humidity attraction and retention is described as either adsorption or absorption, where absorption leads to a chemical change in the desiccant, while adsorption occurs only on the surface of the desiccant, without any chemical change. Most absorbents are liquids, while most adsorbents are solids. The most common absorbents used are aqueous solutions of LiCl, CaCl<sub>2</sub>, LiBr and triethyl glycol. The solution is diluted during the dehydration process and is required to be regenerated before it can be used again. Common solid hygroscopic materials include silica gel and molecular sieves. Hygroscopic solutions have a lower dehumidifying capacity compared to solid hygroscopic materials. However, systems using hygroscopic solutions have many advantages such as ease of handling and low pressure drop in air interaction devices

and in addition, they require lower temperatures for regeneration [73]. Solution regeneration can be performed using solar energy, waste energy or other low-level heat source [74]. Yao [75] studied the use of ultrasound to regenerate hygroscopic materials and achieved up to 45% energy savings during regeneration.

Air conditioning systems with hygroscopic solutions have been rapidly developed in recent years due to their advantages in addressing the latent heat load of buildings, their positive environmental impact (reduction of greenhouse gas emissions, reduction of chlorinated refrigerant fluids and reduced electricity consumption) [69] as well as improving air quality through the removal of a number of air pollutants [74], insect repellent activity [66] and inactivation of airborne fungi [76]. In addition, their cleaning effect in hospital environments is thought to reduce airborne bacteria and remove microparticles [13]. In addition to low vapour pressure, hygroscopic solutions have low viscosity and good heat transfer characteristics. The surface tension of dehumidifying solutions is also important, as it directly affects the static retention and wetting of the dehumidifier-air contact surface. Essentially, hygroscopic solution systems consist of an absorber to dehumidify the air, a regenerator to regenerate the solution and heat exchangers to pre-cool and pre-heat the hygroscopic solution. However, some reports discourage the use of hygroscopic materials for the dehumidification of the greenhouse due to the corrosiveness of certain materials ( $\text{CaCl}_2$ ,  $\text{LiCl}$ ) but this problem can be addressed by replacing the metallic materials of the mechanisms and operating devices with plastic materials, which do not present a corrosion problem. Lycoskoufis and Mavrogiannopoulos [70] used a cross flow dehumidifier with  $\text{CaCl}_2$  solution and concluded that this system, at  $15^\circ\text{C}$  and 80% relative humidity, could absorb water vapour from greenhouse air at a rate of  $4812 \text{ g h}^{-1} \text{ m}^{-2}$  of cross-pad surface. Longo and Gasparella [71] compared three hygroscopic materials ( $\text{LiBr}$ ,  $\text{LiCl}$  and  $\text{KCOOH}$ ) in greenhouse dehumidification, and concluded that, although the  $\text{H}_2\text{O}/\text{LiBr}$  desiccant shows the best performance, the  $\text{H}_2\text{O}/\text{KCOOH}$  solution provides significant energy savings and, also taking into account the favourable aspects of low cost, reduced corrosivity and high environmental compatibility, it seems to be promising as the 'desiccant of the future'.

## **5. Conclusions**

Greenhouse dehumidification is an essential part of greenhouse climate control. High relative humidity is a cause of plant disease development, which ultimately reduces the quantity and quality of yields. The risk of occurrence and development of plant diseases in the greenhouse increases when the plant surface is moist. The higher the relative humidity of the greenhouse air, the higher the likelihood of surface condensation of water vapour on the plants. In theory, surface condensation of water vapour cannot occur when the relative humidity is less than 100% and the temperature of the plants is the same as that of the greenhouse air. However, it has been found that the canopy top temperature is lower due to energy losses through long-range radiation. In this part of the canopy, surface water vapour condensation is likely to occur when relative humidity is high. It has also been found that the more massive organs of the canopy (e.g. fruits, shoots), due to their higher heat capacity (higher mass per surface area), tend to have a lower temperature during periods when the greenhouse air temperature increases, for example at sunrise.

Natural ventilation is an insufficiently controlled greenhouse dehumidification method, increases the heterogeneity of the greenhouse climate and increases energy consumption for heating. The intensity of research on the use of hygroscopic

materials in the dehumidification of greenhouses, which has appeared in recent years, heralds an improvement in their technological excellence and ease of operation, as well as the development of their commercial exploitation. In conclusion, taking into account the current state of technological progress, at the present time, dehumidification of greenhouse air using a heat pump can be considered as the most appropriate solution for dehumidification of both unheated greenhouses and for dehumidification of heated greenhouses. The increase in income, due to the improvement in crop yield by controlling humidity, facilitates the return on investment of a dehumidifying heat pump.

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## Chapter 5

# Greenhouse Systems: A Sustainable Solution to Develop Shrimp Aquaculture Industry

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### Abstract

Within the global aquaculture industry, the sustainable shrimp aquaculture industry is becoming more important as the demand for seafood rises and expands. However, it faces several issues including environmental impact, disease, low productivity, and water quality control. Recent developments in greenhouse (GS) have yielded promising solutions to address these challenges with the development of the shrimp industry. This chapter explores the potential application of GS as an environmentally friendly and sustainable approach for the shrimp aquaculture industry. Firstly, discussing the limitations facing traditional open-pond shrimp farming and their environmental concerns. Then, it highlights the concept of GS and its unique advantages, such as enhanced environmental conditions, disease prevention, and improved water quality protocols. The components of GS required for shrimp aquaculture will be reviewed. The chapter highlights the essential components of GS that are crucial for efficient shrimp aquaculture. Furthermore, it also highlights the integration of other aquatic organisms such as fish, clams, and seaweed, enhancing both sustainability and profitability in the industry. In conclusion, the shrimp GS sector stands poised to surmount existing challenges, mitigate its environmental footprint, and cater to the escalating demand for sustainably produced shrimp. In summary, the shrimp GS sector can address obstacles, reduce its environmental impact, and satisfy the rising demand for shrimp sustainable production.

**Keywords:** food safety and security, *L. vannamei*, IMTA, Pacific whiteleg shrimp, RAS, seafood

### 1. Introduction

By 2050, there will be 9.7 billion people on the planet, an increase of 2 billion [1], necessitating the need to produce high-quality food and improve existing food production systems [2, 3]. Over the past two decades, aquaculture has become a critical contributor to global food security, by adopting intensive culture practices for

diverse species, high controllability, and market adaptability to meet the growing food demand. By 2024, global aquaculture production is expected to reach 122.6 million tonnes, of which 71% are aquatic animals, valued at US\$264.8 billion [4]. Shrimp is the most traded aquatic commodity in the world due to its high economic and nutritional value [5]. Shrimp farming in aquaculture has experienced significant growth rapidly in the past decade, due to the increasing demand in the global commercial shrimp market [6].

In 2022, worldwide shrimp farming yielded 5.17 million tonnes, and this figure is projected to rise to 7.28 million tonnes by 2025, reflecting a 13.6% annual growth rate [7]. The primary commercial shrimp variety, the Pacific white shrimp (*Litopenaeus vannamei*), dominates the industry, comprising 80% of the total global production and is valued at more than \$26.8 billion [8]. Due to its advantages of disease resistance [9], high productivity rates, salinity tolerance, survival, rapid growth, ease of farming, and adaptability to environments [10]. In recent decades, shrimp production has faced many problems affecting its development and growth worldwide, such as overconsumption of water, overfeeding, greenhouse gases (GHGs), and degradation of habitats and aquatic benthic ecosystems, despite its importance in achieving global food security and sustainable development goals. However, although intensification significantly increases GHGs, it also significantly enhances shrimp production [11].

The Industrial Revolution has led to a significant increase in GHG concentrations in the atmosphere along with an increase in population [12]. Moreover, aquatic ecosystems, both natural and human-influenced, such as agricultural or aquaculture activities [13], are significant sources of GHGs [14]. High inputs of residual protein-rich feeds, fecal matter, plankton biomass, and respiration in aquaculture systems contribute to the formation of carbon and nitrogen substrates, leading to the formation of GHGs [15, 16]. Consequently, recent years have seen a significant increase in attention toward GHG emissions from aquatic ecosystems. Farmed crustaceans produce the largest emissions among the species farmed in aquaculture [17]. According to MacLeod et al. [18], shrimp farming in East Asia produced 43.8 million tons of CO<sub>2</sub>-equivalent emissions in 2017, contributing significantly to climate change and GHGs. Therefore, effective regulations are needed for GHGs from aquaculture ponds, as aquatic systems can significantly contribute to climate mitigation efforts [19]. Advances in sustainable aquaculture technologies have led to the development of intensive aquaculture systems, replacing traditional open-pond systems to achieve higher productivity, stability, and profits [20].

Therefore, alternative farming methods can improve the sustainability of shrimp farming by addressing environmental constraints [21], providing cost-effective crop rotations, and reducing production cycles compared to conventional methods [22]. Recently, GS aquaculture systems have gained attention for intensive to ultra-intensive shrimp production due to their advantages in terms of biosecurity, environment, and marketing with zero or limited water exchange, high yields, and controllable temperatures, and can be operated entirely year-round compared to outdoor pond [22].

In this chapter, we broadly review how shrimp farming can be made sustainable by developing alternative farming methods. The rest of the chapter is organized as follows: Section 2 discusses offshore shrimp farming and its environmental concerns; Section 3 discusses the use of GS systems for shrimp farming; Section 4 integrates shrimp with other aquatic organisms; and finally, the use of biofloc technology (BFT) as a promising method for sustainable shrimp farming under GS conditions.

## 2. Outdoor-lined ponds for shrimp culture

Traditionally, shrimp are raised using outdoor earthen ponds, which are the most common type of commercial shrimp farming due to their low construction and operating costs. However, due to their high water consumption and large output of wastes heavy in phosphorus as well as nitrogen, which negatively impacts the aquatic ecosystems they receive, conventional farming methods are rarely sustainable [23]. Earthen pond operations typically begin with fertilization to promote the growth of phytoplankton and sequence zooplankton, which serves as a primary producer in the water ecosystem and aids in consuming nitrogen and other waste [24, 25]. However, the risk of plankton blooms due to potential over-fertilization is a concern [26]. The general approach involves using culture ponds that typically range from 0.5 to 1.5 hectares in size, lined with high-density polyethylene liners (HDPE), and heavily aerated using paddlewheel aerators (28 to 32 horsepower per hectare) [27]. The management practices for shrimp farming vary across different countries. For instance, Ecuador employs a semi-intensive stocking density of 21 shrimp per square meter in a large 6.59-hectare pond, resulting in a production of 1.96 tons per hectare per crop [28].

Additionally, there is now a different method of shrimp farming used worldwide due to the environmental limitations of tank and pond-based shrimp farming, including the proliferation of numerous hazardous and pathogenic strains [29]. Moreover, only one crop cycle is permitted annually due to seasonal low temperatures, which ultimately proves to be more economical than its brief production cycle. With the rapid development of shrimp aquaculture around the world, infectious diseases have become the most common challenge and have resulted in a huge economic loss [30, 31]. Additionally, there is now a different method of shrimp farming used worldwide due to the environmental limitations of tank and pond-based shrimp farming, including the proliferation of numerous hazardous and pathogenic strains. Furthermore, just one crop cycle is permitted annually due to seasonal low temperatures, which ultimately proves to be more economical than the crop's brief production cycle [22]. The management practices for shrimp farming vary across different countries. For instance, Ecuador employs a semi-intensive stocking density of 21 shrimp per square meter in a large 6.59-hectare pond, resulting in a production of 1.96 tons per hectare per crop [22].

*L. vannamei* cultivation systems are classified into four types: extensive, semi-intensive, intensive, and ultra-intensive, which are in average densities of 400–500, 500–5000, 5000–20,000, and 20,000–100,000 kg/ha, respectively [8]. The increase in *L. vannamei* production is primarily driven by the intensification of farming systems, which increase inputs, effluents, and energy demands [13]. Although the intensification of agriculture significantly increases GHGs, it significantly enhances shrimp yield. Therefore, the aquaculture industry is witnessing significant technological advancements to improve production and resource use, reduce environmental impact, and thus enhance sustainability [32]. Examples of these technologies include GS aquaculture systems, integrated polytrophic aquaculture systems, and biofloc technology [33].

Aquaculture provides a variety of techniques for growing aquatic life [34–37]. According to the literature [38–41], **Table 1** examines the subtle distinctions between cutting-edge greenhouse aquaculture systems and traditional aquaculture methods based on a number of important factors. A deeper understanding of the outcomes of choosing between these two aquaculture techniques can be attained by stakeholders by investigating factors like labor intensity, biodiversity impact, and product

Criteria	Traditional aquaculture systems	GS aquaculture systems
Yield per hectare (tons/hectare)	Lower	Higher (> 50%)
Energy consumption	Lower	Higher, but low/ton of yield
Reductions in GHG emissions (%)	High reduction	Lower reduction (> 20%)
Water usage efficiency	Higher	Lower
Contamination	Uncontrolled	Controlled
Utilization of fertilizers	Allowed	Not allowed
Environmentally sustainability	Lower	Higher
Labor intensity	Higher	Lower
Land requirement	Higher	More efficient
Cost-effectiveness	Varies	Based on the initial and operational costs
Product quality	Lower	Higher
Resilience to climate change	Lower	Higher for adaptation

**Table 1.**  
*Comparison of conventional aquaculture systems and greenhouse systems.*

diversification [42, 43]. Decision-makers looking to make educated decisions for sustainable food production and negotiate the intricacies of contemporary aquaculture methods will find this table to be a useful tool [42, 44].

### 3. Greenhouse-lined raceways for shrimp culture

The growth of the world population and the improvement of living standards have increased the demand for high-quality aquatic products such as shrimp, which has accelerated the development of the aquaculture industry [45]. In recent years, shrimp farmers have been facing challenges in shrimp farming due to the high prevalence of pathogens, requiring strategies such as pathogen-free stock rearing, strict quarantine measures, and standardized management. In addition, the environmental challenges posed by shrimp farming in tanks and ponds, including the spread of harmful and pathogenic strains, have necessitated the development of alternative methods [8]. In recent years, GS shrimp farming has expanded worldwide due to its low environmental impact, high return on investment, and water conservation, which allows for longer culture periods and reduced water exchange [46]. In addition, the GS provide abundant natural light and are constructed without heating. There are differences in conditions between indoor and outdoor cultures, with indoor cultures requiring constant light and artificial temperature [47]. Shen et al. [48] reported that a GS pond can somewhat control the spread of pathogens compared to other cultures. Various recent studies have shown that average shrimp biomass ranges from 4 to 6 kg/m<sup>2</sup>, while annual yields from GS streams range from 100 to 120 t/ha, compared to 5 to 7.5 t/ha in conventional ponds [49]. Under GS shrimp culture, an abundance of microorganisms was observed in the intestines of shrimp, with bacilli being the main beneficial bacteria that proliferate throughout the cultivation process [5].

In traditional shrimp farming, one of the most significant consequences of plankton blooms is their contribution to the development of hypoxic conditions [50]. As the plankton populations flourish and subsequently die off, the process of decomposition consumes oxygen, leading to a depletion of oxygen levels in the water [51]. This oxygen depletion can create hypoxic (low oxygen) or anoxic (absence of oxygen) conditions, which are highly detrimental to shrimp health. As the plankton populations flourish and subsequently die off, the process of decomposition consumes oxygen, leading to a depletion of oxygen levels in the water [52]. Moreover, plankton blooms can also impact water quality by altering nutrient dynamics and promoting the accumulation of organic matter. The decomposition of excessive plankton biomass releases nutrients such as nitrogen and phosphorus into the water, leading to eutrophication [53]. Elevated nutrient levels fuel algal growth, further exacerbating the bloom cycle and creating a cascade of negative effects on water quality [54].

On the other hand, the decrease in cyanobacteria and its subsequent impact on shrimp microbiota in shrimp GS is indeed noteworthy [55]. Cyanobacteria are generally diminished in GS systems owing to improved environmental control and the prevalence of beneficial bacteria that outcompete the detrimental strains [56]. This decrease in cyanobacteria within GS systems can be attributed to the meticulously regulated environmental conditions, including controlled nutrient levels and optimized light exposure, which create an environment less conducive to cyanobacterial growth [57]. Furthermore, the competitive advantage exerted by beneficial bacteria, such as certain species of *Bacillus* and *Pseudomonas*, plays a pivotal role in suppressing the proliferation of harmful cyanobacteria. These beneficial microorganisms not only directly inhibit cyanobacterial growth through resource competition but also produce compounds that exhibit algicidal properties, further reducing cyanobacterial populations [58]. Source Tracker analysis suggests that GS farming increases gut microbiota in shrimp, and reduces cyanobacteria in water and sediment, possibly due to temperature, beneficial bacteria, and algae [59]. Cyanobacteria can harm water quality, algal blooms, and toxins. Reducing cyanobacteria in biofloc under GS farming improves the composition of shrimp gut microbiota, promoting healthy growth and immunity. This effect enhances the effectiveness of probiotics in biofloc culture [60]. Li et al. [5] reported that under GS farming, *L. vannamei*'s intestines contain an increase in beneficial microbiota like *Bacillus*. At the same time, an increase in bacteria with the ability to remove nitrogen and phosphorus, such as *Marivita* and *Pseudomonas*, was observed in the water, which further contributed to the increased growth of shrimp.

#### 4. Shrimp integration with other aquatic organisms

In recent years, the aquaculture sector has shifted toward environmentally friendly and sustainable production practices to enhance yield and efficiency in the use of natural resources [61]. Science, technology, and innovation advancements have concentrated on creating environmentally friendly alternatives that align with the Agenda 2030 for Sustainable Development Goals (SDG) [62]. Thus, aquaculture activities can achieve long-term growth by adopting production practices that effectively address current and future challenges. In addition, the expansion of inland aquaculture has raised concerns about the sustainable use of water due to limited resources and increased demand from anthropogenic activities. Recently, the Integrated Multi-trophic Aquaculture System (IMTA) has been gaining popularity [63] as a sustainable aquaculture approach that integrates various species into

ecosystem dynamics [64, 65]; it is a management strategy that aims to increase production and income by improving resource use efficiency by linking the trophic levels of the cultivated species together with nutrient use and organism production, reducing water use compared to monoculture, and thus increasing biomass [66]. The success of IMTA depends on the use of ecologically distinct species with complementary requirements and ensuring appropriate stocking densities for each species [67].

IMTA is not the same as polyculture, which is growing many species without taking into account how they will benefit the environment. The ability of species to maintain ecological balance, on the other hand, is the emphasis of IMTA. This ensures that each species fulfills a distinct role, such as that of a predator, herbivore, detritus, or filter feeder, and that the ecosystem is sufficiently maintained [68]. The application of IMTA is based on the use of waste materials as a source of nutrients intimately associated with the food chain cycle in the culture system [64].

IMTA involves combining complementary species with varying trophic levels to enhance efficiency, reduce waste, and enhance ecosystem functions [28, 61]. For example, tilapia and shrimp show high compatibility due to their diverse feeding habits and spatial distribution, and shrimp consume fish waste [69]; fish filter phytoplankton, reducing low dissolved oxygen levels at night, while shrimp bioturbation recycles nutrients in the water column, increasing phytoplankton production, a natural food source for fish [70]. This process enhances food availability for cultured species and reduces nutrient accumulation in pond bottom sediments [71]. The main motivation for IMTA work is for one species to benefit another by using the waste as a food product for another species, which increases the exploitation of natural resources, achieves a high yield, and maintains supply in the market [8, 22].

Monoculture practices increase phytoplankton and ammonia concentrations and alter dissolved oxygen dynamics due to excess nutrients from uneaten food [67]. On the contrary, the diversity of species in polyculture impacts ecosystem processes such as productivity, decomposition, and nutrient cycling [72, 73]. For example, shrimp culture severely affects ecosystems, suggesting integrated aquaculture practices like polyculture as alternatives for reducing contamination [74]. According to Flickinger et al. [75] and Dantas et al. [69], incorporating shrimp into fish grow-out operations enhances nutrient utilization from inputs, supports the upkeep of favorable water and soil conditions, and enables the utilization of recycled water rich in nutrients with minimal to no water replacement. Similarly, Borges et al., [76] reported that integrated rearing of mullet and shrimp in one pond gives significantly higher growth compared to monoculture. Yokoyama et al. [77] reported that aquaculture wastes are assimilated within the micro-pond environment formed by co-cultured organisms and natural pond organisms in polyculture systems. Hernandez-Barraza et al. [78] reported that shrimp production was higher and disease control was improved in polycultures compared to monocultures. According to Barbosa et al. [79], the polyculture of shrimp and tilapia expressed higher growth and increased disease control, resulting in increased production and economic return compared to Recirculating Aquaculture System (RAS). Poli et al. [80] reported that polyculture of Nile tilapia *O. niloticus* and marine shrimp *L. vannamei* improved growth performance and increased economic efficiency compared to monoculture. da Rocha et al. [81] in mullet and *P. vannamei* reported similar results in mullet and *P. vannamei*. Hoang et al. [82] found that shrimp and fish culture at 10% stocking density improved the growth of mullet, tilapia, and white shrimp. Similarly, Apun-Molina et al. [83] studied the polyculture of *L. vannamei* with tilapia and mullet, respectively, which resulted in increased growth performance, feed utilization, improved yield, and physiological responses. It has been reported an improvement in survival and growth rate [84] and reduction of luminous

pathogenic bacteria *Vibrio harveyi* (in shrimp) cultivated with mollusks including oysters, compared to shrimp monoculture [63]. Several studies suggest that integrated fish and shrimp culture is an alternative to reduce the *Vibrio* spp. Bacteria in water [70, 76]. Borges et al. [76] reported that incorporating mullet into shrimp farming provides a promising solution for reducing solids and has proven successful in improving productivity and water quality. Similarly, Tendencia et al. [85] found that shrimp, when polycultured with tilapia and grouper, showed positive survival due to the antibacterial properties present in the mucus of fish.

Species within IMTA are chosen based on several criteria: (a) their ability to complement each other within the system, (b) their adaptability to environmental conditions, (c) their capacity for efficient bio-mitigation, and (d) market demand and pricing [86]. Moreover, it is essential to determine the species proportions considering their specific functions and the environmental conditions of the ecosystem. This approach aims to optimize the advantages of various trophic levels, diversify activities, ensure environmental sustainability, and guarantee economic feasibility [70]. IMTA combines four categories of aquaculture: (I) fish as feed production, (II) seaweeds as inorganic matter removal, (III) invertebrates as organic matter removal, as filter-feeders, and (IV) benthic invertebrates as sediment cleaners by suspension-feeding and sediment-feeding invertebrates [86, 87].

As a result, environmental issues brought on by aquaculture operations—such as pollution from changing land uses and external changes—can be reduced to a minimum [88, 89]. In addition, because ecological balance has been implemented, IMTA can be employed in nearly all marine and terrestrial aquaculture ponds [64, 66]. Finally, IMTA, or Integrated Multitrophic Aquaculture, is a promising approach for sustainable development, but there is still much to explore in this area. Use of biofloc technology (BFT) as a promising aquaculture method for sustainable shrimp farming under a GS. In the last decade, significant research and development efforts have been dedicated to enhancing the practical implementation of biofloc technology in the super-intensive cultivation of shrimp within enclosed GS at a commercial level [5, 90, 91], providing an alternative to conventional methods in low-temperature regions where shrimp farming is seasonal [92]. GSs offer a cost-effective building option, particularly for integrating BFT systems that aid in temperature regulation [93]. By utilizing GSs, producers can extend the cultivation period throughout the year, leading to increased crop yields [92]. This setup can achieve high shrimp production levels, up to 9.8 kg/m<sup>3</sup> of culture medium, with minimal water consumption under controlled water exchange conditions, surpassing traditional culture methods [94].

There have been tries to cultivate *L. vannamei* at high densities in biofloc systems. Additionally, there have been reports of shrimp at densities as high as 600/m<sup>3</sup>, growth rates of 0.9 grams per week, and survival rates greater than 54% [90, 93, 95]. BFT is one of such novel microbial biotechnologies that have been developed eco-friendly technology not only for higher productivity but also for sustainable development [96] by offering sustainable intensification by producing aquatic organisms with high stocking densities and minimal water use [97], thereby improving water resource management, reduces environmental impact, reduces costs, and maximizes the use of production resources [92]. For example, the amount of water required for tilapia, *Oreochromis mossambicus*, production ranges from 21 to 57.7 m<sup>3</sup> [98]. Not all fish species are suitable for cultivation in the BFT system. Ekasari et al. [99] reported that species with filtering ability and omnivorous and herbivorous feeding habits primarily use microbial communities for food, making them the best species for cultivation.

In recent years, the BFT has been developed as a promising aquaculture method for sustainable shrimp farming [10], and acting as a supplementary food source [100], by detoxifying the ammonia produced by the animals and provide a supplemental nutrition source for shrimp [101]. The BFT system enhances natural productivity in cultivation tanks by promoting the formation of bioflocs, which are suspended particles of microbial communities, which include bacteria, protozoa, microparasites, larvae, feces, dead animal remains, exoskeletons, and other particles present in the tanks [102]. In addition, it has been observed that the use of different carbon sources in the BFT system increases the microbial community and improves the immune status of fish [103]. Biofloc has a high protein content of 25–50% and provides vitamins and minerals. Additionally, it is biologically safe because it has probiotic effects, which reduce the impact of pathogenic bacteria and improve growth [27]. Bioflocs, which are consumed by shrimp as natural food, can significantly reduce their protein requirements in BFT systems, reducing reliance on high-protein commercial feeds and production costs and contributing to increased shrimp growth and health [10].

A study by Browdy [104] reveals that the use of biofloc for shrimp farming can reduce operating costs by 30% due to reduced feed intake. Similarly, Avnimelich et al. [90] found that reducing the protein content of the diet of hybrid tilapia by 10% points in BFT systems could reduce feed expenditure by 46%. According to Lara et al. [105] and Papadopoulos et al. [10], they found increased growth and productivity of *P. vannamei* shrimp in biofloc systems generated in GS ponds compared to cultivation using conventional methods. Similarly, Wyban et al. [106] reported that when shrimp were cultured in a biofloc system under GS conditions, there was an increase of 5.14%/day and 1.45 g/week in weight growth rate and weight gain, respectively. [107] found that *P. vannamei* individuals stocked at 500 shrimp/m<sup>3</sup> in a biofloc system under GS conditions had an SGR of approximately 7.4% per day. Vungarala et al. [108] found that shrimp grow faster and have higher tissue protein levels due to the additional protein generated from recycled waste in a zero-water-exchange BFT culture system [75]. In addition, the enzymes in bioflocs can affect digestive enzyme activity, helping to break down organic compounds in marine shrimp, as shown in shrimp food studies [91]. Zhang et al. [59] found *Pseudomonas* strains have 100% nitrite removal capacity in high nitrite environments, with lower nitrite content in GS cultures, possibly due to increased *Pseudomonas* abundance, and have an indirect positive effect on gut microbiota and healthy shrimp growth by improving water quality in biofloc under GS cultures.

The combination of biofloc and integrated enhances growth and disease control, reduces feed and water inputs, and reduces waste production. Poli et al. [80] reported that the integration of Nile tilapia (*O. niloticus*) and marine shrimp (*L. vannamei*) in a biofloc system improved growth performance and increased economic efficiency compared to monoculture. da Rocha et al. [81] in mullet and *P. vannamei* reported similar results in mullet and *P. vannamei*. Likewise, Liu et al. [109] conducted an integrated shrimp and spotted scat in biofloc.

## 5. Limitations and future of biofloc technology in aquaculture

Biofloc technology presents a cost-effective substitute for reducing fish commercial diets while also mitigating any environmental issues [110]. The application of BT in aquaculture has many advantages over other conventional fish farming technologies. The beneficial effects of biofloc include the following: (a) maintaining water quality by assimilating nitrogen from food waste; (b) providing a natural food source

that is rich in protein, which reduces the feed conversion rate (FCR); (c) reducing feed costs; (d) reducing wastewater discharges and pathogens. BT application in aquaculture offers numerous benefits over other traditional fish-rearing systems. These benefits include: (1) preserving water quality through the assimilation of nutrients from unconsumed feed and fish wastes, (2) offering a naturally occurring, high-protein food source that lowers the FCR, (3) lowering feed costs, (4) lowering pathogens, (5) lowering wastewater discharges, (6) minimizing the rate of water refilling, and (7) increasing production [111]. Probiotics and their cooperative relationships within this microecosystem are an important factor in the beneficial effects of BF systems. Probiotics flourish in bioflocs and rule this microecosystem when the right conditions are met. Here, they perform essential tasks like immunological activation, growth promotion, pathogen inhibition, and nutrient recycling [97] and serve as beneficial gut microflora [112]. Conversely, there are several drawbacks associated with this approach [113], including:

- a. Dependence on a consistent electricity supply.
- b. A longer start-up period of 4–6 weeks for floc development compared to recirculating aquaculture systems (RAS) and other conventional methods.
- c. The necessity of constructing GSs in some cases to regulate temperature and prevent excessive seaweed growth.
- d. Requirement for skilled personnel to operate the system effectively.
- e. Regular monitoring of water quality through laboratory testing.
- f. Continuous monitoring of floc volume, ammonia levels, and oxygen saturation.

These challenges can be addressed through operational experience, beginning with lower stocking densities and gradually gaining a comprehensive understanding of the key water quality parameters that require regulation. Despite these hurdles, utilizing this technology is often more cost-effective than implementing a full aquaculture recirculation system due to lower construction costs [114].

The system is convenient, easy, and profitable for nitrogen removal, but further research is needed to improve its technical aspects for successful implementation [90]. For example, advanced monitoring systems for floc composition and characteristics are developed to enhance understanding and promote sustainable aquaculture worldwide for future generations [87].

## **6. Conclusion and future prospective**

In conclusion, GSs offer a promising solution for sustainable shrimp aquaculture, addressing challenges like disease control and environmental impact. The prospects for GS look bright, with advancements in technology enhancing productivity and sustainability. Embracing GS signifies a shift toward eco-friendly practices in aquaculture, requiring collaborative efforts to drive widespread adoption and create a more resilient shrimp farming sector. This transition toward innovative farming methods holds the potential to revolutionize the industry, paving the way for a future where efficient, sustainable seafood production is not just a goal but a reality.

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## **Conflict of interest**

The authors declare no conflict of interest.

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Section 4

Knowledge Transfer and  
Adoption in Practical Settings

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## Chapter 6

# Climate-Smart Agriculture in Action: Insights from the National Horticultural Research Institute on Awareness, Utilization, and Constraints

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### Abstract

This study examines the awareness and utilization of climate-smart agricultural practices (CSAP) among scientists and technical staff at the National Horticultural Research Institute (NIHORT) in Nigeria, emphasizing their critical role in farmer education. Data were collected from 60 respondents through a combination of qualitative and quantitative methods, yielding 53 analyzable responses. The analysis employed descriptive statistics to evaluate levels of participation and awareness. Key findings indicate that 71.7% of respondents are involved in field research, and 56.6% incorporate CSAP into their planning processes. Despite a high level of awareness regarding various practices, actual utilization remains low, with home gardening identified as the most frequently employed practice (56.6%). Inadequate training (50.9%) emerged as a significant barrier, along with insufficient government support and high implementation costs. The study concludes that, although awareness of CSAP exists, its practical application is insufficient, highlighting the need for in-house sensitization and targeted training initiatives to improve utilization among staff. Recommendations include the organization of workshops and institutional advocacy to enhance the integration of CSAP in horticultural research and education for farmers.

**Keywords:** productivity, greenhouse gas emissions, horticulture, adaptation, mitigation

### 1. Introduction

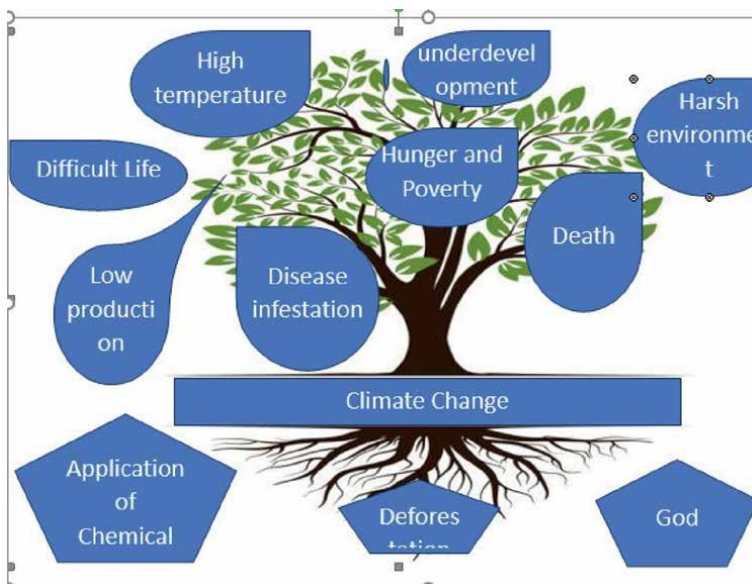
Climate is the average weather conditions in a specific region for approximately 30 years [1, 2]. Climate change refers to long-term shifts in temperatures and weather

patterns, which can occur due to both natural and anthropological influences. Natural factors include variations in solar cycles, which can significantly affect Earth's climate. Solar cycles, characterized by fluctuations in solar radiation and sunspot activity, can lead to changes in global temperatures and weather patterns over extended periods [3, 4]. For instance, periods of increased solar activity may contribute to warmer temperatures, while reduced solar output can lead to cooling trends.

In contrast, human activities have emerged as the primary drivers of contemporary climate change, predominantly through the combustion of fossil fuels such as coal, oil, and gas for energy production, manufacturing, transportation, and building operations. Additional human-induced factors contributing to greenhouse gas emissions include urbanization, agricultural practices, and deforestation [5, 6]. Climate change is causing more frequent and intense storms, floods, melting of ice glaciers, sea-level rise and wildfires in different parts of the world. News from the world mentioned that For example, in 2022, Europe experienced record-breaking heat waves, the United States and South Korea experienced record-breaking flooding, and Pakistan experienced flooding that led to stagnant water and unsanitary conditions—also, wildfire in Canada between 2023 and 2024.

In Nigeria, increasing climate variability has resulted in more intense and erratic rainfall patterns, leading to flash floods, landslides, gully erosion, and aggravating land degradation. These changes have detrimental effects on agriculture and food security, depleting national resources and threatening human infrastructure [7]. The implications of climate change are profound and widespread, manifesting in flooding, erratic rainfall, heatwaves, food scarcity, increased susceptibility to pests and diseases, health risks, poverty, and displacement [8]. The urgency of addressing climate change as a global concern cannot be overstated.

A previous study conducted on farmers' perceptions of the effect of climate change on citrus and tomato production in Nigeria was summed up in a problem tree (**Figure 1**) that explains how farmers perceived climate change [1].



**Figure 1.** Perception of farmers on the effect of climate change.

In order to mitigate and alleviate the impacts of climate change, proactive adaptation strategies are essential. One such approach is Climate-Smart Agriculture (CSA), a suite of agronomic practices designed to enhance the resilience and productivity of agricultural systems vulnerable to climate change. As defined by the Food and Agriculture Organization (FAO), CSA encompasses “agriculture that sustainably increases productivity, enhances resilience to climate change, reduces, and/or removes greenhouse gas emissions, and contributes to the attainment of national food security and development objectives” (FAO, as cited in [9, 10]). The implementation of CSA practices is critical for building climate resilience, promoting sustainable agriculture, and ensuring food security in the face of climate change.

Climate-smart agriculture (CSA) is not a solution to climate change itself; rather, it addresses many of the secondary and tertiary issues stemming from climate-related threats and shocks. CSA represents a comprehensive strategy for managing farmlands, crops, livestock, and forests to counteract the negative impacts of climate change on agricultural productivity. The three primary objectives of CSA are to enhance productivity, promote adaptation, and facilitate mitigation [11]. This integrated approach tackles the interconnected challenges of food security and escalating climate change by managing landscapes, cropland, livestock, forests, and fisheries. Ultimately, CSA aims to achieve increased productivity, enhanced resilience, reduced emissions, and broader development goals in the context of a changing climate and rising food demand.

Globally, the repercussions of climate change are profound, leading to increased weather variability, extreme weather events, and shifts in agricultural viability. These changes threaten food security, aggravate poverty, and challenge sustainable development efforts. As nations grapple with these global challenges, the effects are acutely felt in specific regions, particularly in developing countries like Nigeria.

In Nigeria, climate change manifests through severe weather patterns, impacting agricultural productivity and food security. The country faces specific challenges such as erratic rainfall, prolonged droughts, and increasing temperatures, which threaten the livelihoods of farmers and the sustainability of agricultural practices. Climate-smart agriculture techniques and practices, including conservation agriculture, improved crop varieties, soil and water management, irrigation, agroforestry, post-harvest management, integrated pest management, nutrient management, and livestock management, are essential in addressing these challenges.

Research has shown that farmers across various regions in Nigeria are aware of Climate-Smart Agricultural Practices (CSAP) [12, 13]. However, there is a notable gap in studies assessing the awareness and implementation of CSAP among scientists and technical staff in research institutes responsible for educating farmers on these practices. This gap notes the importance of NIHORT, a key horticultural stakeholder in Nigeria, which has been purposely selected for this study. Horticultural crops, including leafy and fruity vegetables, fruits, spices, and ornamental plants, are particularly vulnerable to the impacts of climate change.

Over the years, NIHORT has collaborated with farmers in both adopted and non-adopted villages, as well as in secondary schools such as Baptist Grammar School, St. Teresa's, Oba Abas, and Anwarul Islam in Oyo State, Nigeria. Collaborators include Agricultural Development Projects (ADPs), non-governmental organizations such as the Justice Development and Peace Commission, and various women and youth groups, among others. To effectively mitigate and adapt to climate change while enhancing productivity, NIHORT must take responsibility for ensuring that its stakeholders are adequately informed about and utilize specific practices.

As a Yoruba adage states, “Eni to ma daso fun ni torun re laa koko wo,” meaning “you cannot give what you don’t have.” This emphasizes the need for this study on the utilization of climate-smart agriculture practices among scientists and technical staff at NIHORT. By fostering awareness and implementation of CSA, NIHORT can play a pivotal role in addressing the challenges posed by climate change in Nigeria.

The objectives of the study were to:

1. Identify the personal characteristics of the scientists and technical staff.
2. Identify research activities scientists and technical staff are involved in.
3. Assess scientists and technical staff’s level of awareness and utilization of climate-smart agriculture practices in their research and field activities.
4. Assess considerations given to climate-smart practices in their research and field activities planning.
5. Outline constraints to the use of CSAP in their research and field activities.

## **2. Methodology**

### **2.1 The study area**

The National Horticultural Research Institute (NIHORT) in Ibadan originated as the National Fruit and Vegetable Research and Development Centre (NFVRDC), established with the support of the UNDP/FAO project NIR/72/007. Pursuant to the Federal Government Agricultural Research Institute Establishment Decree Order No. 35 of June 1975, the center was transformed into NIHORT, concurrently with the establishment of other agricultural research institutes.

NIHORT has undergone several administrative transformations since its inception. Initially, it came under the National Science and Technology Development Agency (NSTDA) following the promulgation of Decree No. 5 in January 1977. Subsequently, the Institute was transferred to the Ministry of Science and Technology in January 1980, as a result of the Science and Technology Bill of 1980. However, in 1996, the Institute’s administrative oversight shifted to the Federal Ministry of Agriculture and Rural Development. Finally, with the enactment of the Agricultural Research Council of Nigeria Act 1999, NIHORT came under the purview of the Agricultural Research Council of Nigeria (ARCN) in 2006.

NIHORT’s headquarters is strategically located on a 310-hectare site at Jericho Reservation Area, Idi-Ishin, Ibadan, within the rainforest zone of Southwestern Nigeria. In addition to its headquarters, the Institute operates a network of research stations, comprising three outstations and two experimental stations. Notably, one of the outstations is situated on an 810-hectare site at Mbato Okigwe, Imo State, within the humid zone of Southeastern Nigeria.

- The second out-station is situated on 110 hectares of land at Bagauda, Kano state in the semi-arid zone of North-western Nigeria.
- The third out-station is on a 15.6 hectare of land in Otukpa, Benue State in the derived savanna belt of North Central of Nigeria.

- One experimental station is on 126 hectares of land at Dadinkowa, Gombe State while the second one is situated on 75 hectares of land at Riyom near Jos (the mid-altitude zone), Plateau State.
- The proposed third experimental station is located at Ozalla Owan –West LGA of Edo state in the tropical rain forest zone of Nigeria.

NIHORT envisions a thriving Nigerian horticultural sector, producing high-quality crops and products for local and international markets, with attendant health, industrial, and employment benefits. To achieve this, NIHORT's mission is to develop sustainable production and utilization systems for horticultural crops, focusing on excellence in research and development of fruits, vegetables, spices, ornamentals, and aromatic plants. The Institute's mandate encompasses research in Genetic Improvement, Production Technologies, Processing, Storage, Utilization, and Marketing (GIPTPSUM) of horticultural crops, prioritizing fruits, vegetables, ornamentals, spices, and medicinal and aromatic plants of nutritional and economic significance.

## 2.2 Sampling procedure

As of 2023, the documented total staff population was 870; however, the actual number present during this study was 600 due to various factors, including retirements, leaves of absence, and the phenomenon known as the “Japa” syndrome which can be translated as “brain drain.” Consequently, a sample size representing 10% of the population was utilized. The study's population comprised research scientists and technical staff from both the NIHORT headquarters and its outstations. A total of 60 respondents were selected for sampling, of which 53 completed and returned the survey instrument. Among the respondents, 27 were scientists, while the remainder consisted of technical staff.

The method of sampling in this study was influenced by a notable decrease in the study population, which can be attributed to factors such as retirements, leaves of absence, and the phenomenon known as the “Japa” syndrome, often referred to as “brain drain.” As of 2023, while the documented total staff population was 870, the effective number present during the study was reduced to 600. This reduction in the available population directly impacted the sampling method and its representatives.

To ensure a robust sampling approach, a sample size representing 10% of the active population was determined, resulting in the selection of 60 respondents. This percentage was chosen to balance the need for statistical significance with the constraints of the reduced population. However, it is important to acknowledge that the decrease in staff numbers may have implications for the representativeness of the sample.

The study's population consisted of research scientists and technical staff from both the NIHORT headquarters and its outstations. While the initial intention was to capture a diverse range of perspectives from these groups, the reduced sample size limits the diversity and comprehensiveness of the findings. Specifically, the attrition of staff leads to an underrepresentation of certain demographics or areas of expertise, particularly those who left had unique skill sets.

Out of the selected 60 respondents, 53 completed and returned the survey instrument, yielding a response rate of approximately 88.3%. Among these respondents, 27 were scientists, while the remaining respondents were technical staff. While this

distribution provides valuable insights into the experiences and perceptions of both groups, this study also recognizes that the sample may not fully reflect the broader staff population, specifically that the retired and absent members held significant roles and contributed to particular research areas.

### **2.3 Data collection and analysis**

Data for the study were collected through a mixed-methods approach, incorporating both quantitative and qualitative techniques. The quantitative data were gathered using a Google Form questionnaire, while qualitative insights were obtained through interviews with key informants.

In the analysis of the Degree of Utilization, scores were assigned based on usage frequency, with “rarely used” designated as 1 and “often used” as 2. Similarly, for the assessment of constraint severity, scores were assigned as follows: “Not Severe” received a score of 1, “Severe” was given a score of 2, and “Very Severe” was assigned a score of 3.

The scores for both the Degree of Utilization Scores (DUS) and the Severity of Constraints Scores (SCS) were aggregated separately to facilitate comparative analysis. Items with the highest scores were ranked first, while those with the lowest scores were ranked last, allowing for a clear identification of trends and patterns in the data.

To ensure rigor in the results, various statistical techniques were employed to analyze the data. These included measures of central tendency and dispersion, which provided insights into the overall distribution and variability of the scores. Additionally, regression analysis was utilized to explore potential relationships between the DUS and the SCS, thereby boosting the depth of understanding regarding the factors influencing the utilization of practices within the study population.

## **3. Results and discussion**

### **3.1 Personal characteristics of the participants**

**Table 1** shows that males make up 56.6% of the sample, compared to females comprising 43.4%. A considerable percentage of the respondents (86.8%) are married, and the majority (60.4%) of them possess postgraduate degrees. This result is in line with the study of [14] who found that 87.2% of the respondents were married in their study of the effects of training and development on employees’ performance at Forestry Research Institute Nigeria. On the contrary to the above result on education, 26.5% possess Postgraduate education. As indicated by the largest percentage of participants (32.0%), their years of service spanned from 15 to 19 years. Researchers comprise 50.9% of the total number of staff members, which represents the staff category with the highest frequency. This result implies that people who were interviewed are mostly experienced and have a very good knowledge of the institute; thus, they will be able to engage stakeholders if the need arises.

### **3.2 Involvement in research activities**

**Table 2** presents the involvement of respondents in field and research activities, with 71.7% of respondents indicating that they are involved, while 28.3% are not.

Variables	Frequency	Percentage (%)
<i>Sex</i>		
Male	30	56.6
Female	23	43.4
<i>Age</i>		
20–29	6	11.3
30–39	14	26.4
40–49	22	41.5
50–59	9	17.0
60–69	2	3.8
<i>Marital status</i>		
Married	46	86.8
Single	7	13.2
<i>Level of education</i>		
School Cert.	1	1.9
Graduate	20	37.7
Postgraduate	32	60.4
<i>Years in service</i>		
<5	15	28.3
5–9	5	9.4
10–14	10	18.9
15–19	17	32.0
20–24	3	5.7
25–29	3	5.7
<i>Staff category</i>		
Field staff	1	1.9
Agric superintendent	4	7.5
Technologist	12	22.6
Researchers	27	50.9
Others	9	17.0

Source: *Field Work*, 2023.

**Table 1.**  
 Personal characteristics of the participants (n = 53).

This implies that scientists and technical staff work hand-in-hand for research and development in the Institute. Scientists do not work in isolation from technical staff.

The findings above align with the assertions of Frank et al. [15], in their article, “The Key Attributes of Successful Research Institutes.” They posited that every individual within a research institute, regardless of their role, contributes to its scientific output and productivity. While researchers tackling complex scientific questions are crucial, their efforts are optimized by the institute’s overarching strategy, synergies

Involvement	Frequency	Percentage(%)
No	15	28.3
Yes	38	71.7

*Source: Field Work, 2023.*

**Table 2.**  
*Involvement in research activities (n = 53).*

with facilities and platforms, and robust administrative and corporate support. This perspective underscores the importance of a collaborative and integrated approach to driving research excellence.

### 3.3 Consideration for CSAP while planning research activities

**Table 3** shows the consideration given to climate-smart agriculture practices while planning research and field activities. The data indicates that 56.6% of respondents consider these practices, while 43.4% do not consider them practices. This implies that an average number of field and research staff consider CSA while planning for research activities, this level of consideration is sub-optimal and may impede the development of research activities. If the Institute is at this level, it then implies that there could be great challenges in enlightening the horticultural stakeholders. Therefore, it should be a point of priority to take into consideration the issue of CSAP while thinking or planning any horticultural research activities.

### 3.4 Awareness of climate-smart agriculture practices

**Table 4** illustrates the respondents' awareness of various climate-smart agriculture practices. The majority of respondents demonstrated familiarity with the identified CSAP, with awareness levels for biochar and biogas slightly exceeding the average at 58.5% and 54.7%, respectively. In contrast, a previous study conducted by Oyedele et al. [16] on the awareness and accessibility of climate-smart agricultural practices among citrus producers in Oyo State reported that only 48.6, 34.7, 34.7%, and 31.9% of respondents recognized shifting cultivation, diverse crop establishment methods, agroforestry, crop rotation, and cover crop usage as agricultural practices, albeit without acknowledging their potential as climate-smart strategies. This suggests that the majority of scientists and technical personnel at NIHORT are cognizant of the CSAP available both within the institute and externally, indicating the accessibility of these practices at NIHORT.

Consideration	Frequency	Percentage(%)
No	23	43.4
Yes	30	56.6

*Source: Field Work, 2023.*

**Table 3.**  
*Putting agricultural climate-smart practices into consideration while planning research activities (n = 53).*

Climate-smart practices	No	Yes
Minimum or zero tillage practice	17 (32.1)	36(67.9)
Use of organic fertilizer	5 (9.4)	48(90.6)
Shifting cultivation	12 (22.6)	41(77.4)
Use of improved seeds/seedlings	3 (5.7)	50((94.3)
Integrated pest management (IPM)	6 (11.3)	47 (88.7)
Crop rotation	8 (15.1)	45(84.9)
Erosion and runoff control	10 (18.9)	43(81.3)
The use of cover crops	10 (18.9)	43(81.3)
Agroforestry	13 (24.5)	40(75.5)
Harvesting of rainwater	19 (35.8)	34(64.2)
Composting	12 (22.6)	41(77.4)
Home Gardening	5 (9.4)	48(90.6)
Biochar and Biogas	22 (41.5)	31(58.5)
Mopping up plantain waste for soap production	24 (45.3)	29(54.7)
Biopesticides	13 (24.5)	40(75.5)
Treated manure and nitro-fixing trees	18 (34.0)	35(66.0)
Intercropping	8 (15.1)	45(84.9)
Container gardening and encased beds	18 (34.0)	35(66.0)
Efficient irrigation	7 (13.2)	46((86.8)
Crop diversity	12 (22.6)	41(77.4)
Mulching	5 (9.4)	48(90.6)
Flood-tolerant plant varieties	19 (35.8)	34(64.2)
Heat-tolerant varieties	16 (30.2)	37(69.8)
Shade house	18 (34.0)	35(66.0)
Boundary trees	19 (35.8)	34(64.2)
Contour planting	19 (35.8)	34(64.2)

*Source: Field Work, 2023.*  
*Percentage values are in parentheses.*

**Table 4.**  
*Awareness of different climate-smart practices (n = 53).*

### 3.5 Usage and degree of use of climate-smart agriculture practices

**Table 5** presents the findings regarding the utilization and frequency of various CSAPs among respondents. Home gardening emerged as the most widely adopted practice, with a usage score of 71, followed by organic fertilizer application at 63, and crop rotation at 62. These results indicate that, despite a general awareness of CSAP, the actual degree of utilization among respondents remains relatively low. The reasons for the low level of usage may be seen in the constraints to use, which were later identified in the study. The implications of these findings underscore the significant potential for enhancing the adoption of climate-smart

Climate-smart practice	No	Degree of use (DU)			Rank
		Yes/Often	Yes/Rarely	*DUS	
Minimum or zero tillage practice	6 (11.3)	15 (28.3)	15 (28.3)	45	14th
Use of organic fertilizer	9 (17.0)	24 (45.3)	15 (28.3)	63	2nd
Shifting cultivation	13 (24.5)	13 (24.5)	15 (28.3)	41	19th
Use of improved seeds/seedlings	16 (30.2)	26 (49.1)	8 (15.1)	60	5th
Integrated pest management (IPM)	15 (28.3)	19 (35.8)	13 (24.5)	51	8th
Crop rotation	8 (15.1)	25 (47.2)	12 (22.6)	62	3rd
Erosion and runoff control	13 (20.8)	20 (37.7)	10 (18.9)	50	10th
The use of cover crops)	11 (20.8)	19 (35.8)	13 (24.5)	51	8th
Agroforestry	13 (24.5)	21 (39.6)	6 (11.3)	48	12th
Harvesting of rainwater	7 (13.2)	16 (30.2)	11 (20.8)	43	17th
Composting	14 (26.4)	19 (35.8)	8 (15.1)	46	13th
Home Gardening	7 (13.2)	30 (56.6)	11 (20.8)	71	1st
Biochar and Biogas	10 (18.9)	11 (20.8)	10 (18.9)	32	25th
Mopping up plantain waste for soap production	8 (15.1)	17 (32.1)	4 (7.5)	38	21st
Biopesticides	13 (24.5)	22 (41.5)	5 (9.4)	49	11th
Treated manure and nitro-fixing trees	10 (18.9)	20 (37.7)	5 (9.4)	45	14th
Intercropping	14 (26.4)	23 (43.4)	8 (15.1)	54	7th
Container gardening and encased beds	11 (20.8)	18 (34.0)	6 (11.3)	42	18th
Efficient irrigation	13 (24.5)	28 (52.8)	5 (9.4)	61	4th
Crop diversity	16 (30.2)	20 (37.7)	5 (9.4)	45	14th
Mulching	15 (28.3)	25 (47.2)	8 (15.1)	58	6th
Flood-tolerant plant varieties	19 (35.8)	16 (30.2)	—	33	24th
Heat-tolerant varieties	16 (30.2)	14 (26.4)	14 (26.4)	37	22nd
Shade house	18 (34.0)	12 (22.6)	17 (32.1)	40	20th
Boundary trees	19 (35.8)	13 (24.5)	15 (28.3)	36	23rd
Contour planting	19 (35.8)	14 (26.4)	12 (22.6)	30	26th

Source: *Field Work*, 2023.

\*DUS: Degree of Use Score.

Percentage values are in parentheses.

**Table 5.**

*Usage and degree of use of different climate-smart practices.*

agriculture practices to mitigate the adverse effects of climate change on agricultural productivity and related activities. Supporting this observation, a study by Adebisi-Adelani et al. [17] assessed the utilization of climate-smart agricultural practices among plantain farmers in the Ose Local Government Area of Ekiti State, Nigeria. Their research revealed that, based on mean scores, the majority of respondents reported utilizing integrated pest management ( $\chi = 2.30$ ), followed by improved seed varieties ( $\chi = 2.04$ ), minimum or zero tillage ( $\chi = 2.00$ ), and various methods of crop establishment ( $\chi = 1.94$ ). Additionally, the use of organic

fertilizer ( $\chi = 1.86$ ), irrigation management ( $\chi = 1.83$ ), soil erosion and runoff control ( $\chi = 1.41$ ), cover crops ( $\chi = 1.31$ ), crop rotation ( $\chi = 1.20$ ), shifting cultivation ( $\chi = 1.03$ ), rainwater harvesting ( $\chi = 0.80$ ), and agroforestry ( $\chi = 0.76$ ) were also noted. Collectively, these findings suggest that while respondents are employing certain climate-smart agricultural practices, the levels of utilization are insufficient to effectively address the challenges posed by climate change. This indicates a critical need for targeted interventions to promote the widespread adoption of CSAP among agricultural stakeholders.

### 3.6 Constraints to the use of climate-smart agricultural practices

**Table 6** delineates the constraints to the implementation of CSA practices, with inadequate training emerging as the most significant barrier, evidenced by a severity constraint score of 109. This is closely followed by insufficient government support, which scored 101, and the high cost of practices, which received a score of 96. These findings are corroborated by Ekpa et al. [18], who identified a lack of trained personnel available to assist rural farmers in the technical demonstration of CSA practices. Likewise, Adebisi-Adelani et al. [17] found that the majority of respondents reported limited government support ( $\chi = 2.74$ ) and high costs associated with CSA practices ( $\chi = 2.41$ ). Additionally, respondents indicated challenges such as financial constraints ( $\chi = 2.41$ ), insufficient training on the application of CSA practices (mean score = 1.36), unavailability of improved planting materials ( $\chi = 1.33$ ), difficulties in the practical application of CSA methods ( $\chi = 1.23$ ), lack of knowledge regarding CSA practices ( $\chi = 1.20$ ), and issues related to the division of labor ( $\chi = 1.11$ ).

These findings underscore the critical challenges encountered in the promotion of climate-smart agriculture and highlight the urgent need for targeted interventions. Academic literature supports the notion that effective training programs, enhanced government support, and financial assistance are essential to overcoming these barriers [19]. Further, the integration of community-based approaches and stakeholder engagement has been shown to facilitate the adoption of CSA practices, thereby enhancing agricultural resilience in the face of climate change [11, 20]. Addressing these constraints through comprehensive policy frameworks and collaborative efforts is imperative for the successful implementation of climate-smart agriculture.

Constraints	Degree of severity						Rank
	No	Yes	NS	S	VS	SS	
High cost of the practices	6(11.3)	47(88.6)	12(22.6)	21(39.6)	14(26.4)	96	3rd
Inadequate training in usage	3(5.7)	50(94.3)	7(13.2)	27(50.9)	16(30.2)	109	1st
Lack of knowledge	8(15.1)	45(84.9)	9(17.0)	22(41.5)	14(26.4)	95	4th
Difficulty in application	7(13.2)	46(86.9)	21(39.6)	19(35.8)	6(11.3)	77	5th
Lack government support	6(11.3)	47(88.6)	13(24.5)	14(26.4)	20(37.7)	101	2nd

*Source: Field Work, 2023. (NS – Not Severe; S – Severe; VS – Very Severe; and SS – Severity Constraint Score). Percentage values are in parentheses.*

**Table 6.**  
*Constraints to the use of climate-smart agricultural practices.*

	Frequency	Percentage (%)
Meaning of climate change: As long-term variation in climate parameters	6	100
When have you started noticing climate change?	1	33.3
< 5 years	2	66.7
5–10 years	2	66.7
11–15 years	1	33.3
>15 years		
Awareness of CSA availability in the Institute	5	83.3
Can you put the cost in CSA	6	100

*Source: Field Work, 2023.*

**Table 7**

*Interview with key selected informants.*

### 3.7 Result from the key informants interview (qualitative data)

Six important personalities were interviewed on the subject in question All (100.0%) of them agreed to the fact that Climate change is a long-term variation in climate parameters. They stated that it is a departure from what is to do with factors such as rainfall, wind and humidity, they further mentioned the emergence of pests and diseases. Also, Climate change affects our social life and the food we eat. It is a change in the totality of weather characterized by ozone layer depletion, melting of ice, excessive heat and extreme weather events. When asked when they started noticing a climate change 66.7% mentioned that they have been noticing a change in climate in the past 11–15 years and 33.3% over 15 years. They further stated that at first it was speculated but scientifically it was proven that Climate change is real. When asked about their awareness of Climate-Smart Adaptation strategies available in the Institute, 83.3% affirmed the fact that they are aware of CSA practices available in the Institute. All (100.0%) of the key informants stated that they are ready to put the cost on CSA practices (Table 7).

## 4. Conclusion

This study underscores the vital importance of awareness and utilization of CSAP among scientists and technical staff at NIHORT, Nigeria. The research findings indicate a significant level of engagement in research activities, with 71.7% of respondents actively participating in CSAP-related research and 56.6% incorporating these practices into their planning processes. However, despite this awareness, the practical application of CSAP remains surprisingly limited, with home gardening emerging as the most frequently adopted method.

The study identifies several key constraints hindering the effective utilization of CSAP, including inadequate training, insufficient government support, and high implementation costs. These barriers highlight a critical disconnect between awareness of climate-smart practices and their actual application in agricultural settings. This gap poses a substantial challenge to enhancing agricultural resilience and productivity in the face of climate change. Addressing these challenges is imperative for promoting sustainable agricultural practices that effectively mitigate the impacts of climate change on Nigeria's horticultural sector.

## **5. Recommendations**

1. In-house sensitization is essential for increasing awareness and understanding of CSAP among staff. By ensuring a shared knowledge base, NIHORT can create a unified approach to implementing CSA, ultimately enhancing its effectiveness in research and outreach efforts.
2. Given that inadequate training is identified as the most significant constraint to CSAP utilization, developing comprehensive training programs tailored to the specific needs of NIHORT staff is vital. These initiatives should focus on practical applications of CSA, ensuring that employees are equipped with the necessary skills and knowledge to implement these practices effectively.
3. Workshops serve as a platform for knowledge exchange and skill development, allowing staff and stakeholders to engage with CSA concepts actively. Collaborative efforts can facilitate partnerships with other organizations and experts, enhancing resource sharing and innovation in climate-smart practices.
4. Addressing the financial barriers associated with the implementation of CSAP is crucial for successful adoption. By advocating for increased government support and funding, NIHORT can help ensure that necessary resources are available for both staff training and the practical application of CSA, thereby promoting sustainable agricultural practices.
5. Establishing robust monitoring and evaluation mechanisms will allow NIHORT to assess the effectiveness of training programs and sensitization efforts. This data-driven approach can inform future initiatives, ensuring continuous improvement and adaptation of strategies to meet the evolving challenges of climate change in agriculture.

## **6. Future research directions**

Future studies should focus on longitudinal assessments of the impacts of CSAP implementation on agricultural productivity and resilience. Investigating socio-economic factors influencing the adoption of these practices among farmers will provide deeper insights into effective strategies for promoting climate-smart agriculture. Furthermore, examining the role of government policy and support mechanisms in facilitating CSAP adoption can enhance the effectiveness of initiatives aimed at achieving food security and climate resilience in Nigeria. Additionally, exploring how research participation influences CSA implementation may yield valuable insights for optimizing training and outreach efforts, ultimately contributing to a more sustainable agricultural framework in the face of climate variability.

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