Greenhouse Revolution: Pioneering Cultivation Techniques for Tomorrow

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Greenhouse technology in agriculture promises a bright and sustainable future. It does not just boost crop yields; it paves the way for a more efficient and sustainable way of growing food. It helps plants produce more, enhances quality, increases the value of produce, and significantly reduces loss. Greenhouse farming enables us to grow crops year-round, regardless of seasonal variations. Greenhouses can control the humidity and temperature of the environment inside them, opening up a world of possibilities for agriculture. Farmers can overcome the challenges of a growing population and climate change affecting food production with various innovations in greenhouse farming. Greenhouse technology has transformed modern agriculture by creating controlled environments that enhance plant growth and boost crop yields. The future of greenhouse technology is not just promising; it is optimistic. Advancements in automation, artificial intelligence, and data analytics are transforming greenhouses into highly efficient and intelligent systems. Intelligent sensing, artificial intelligence, vertical farming, robotics, and data analytics will shape the next generation of greenhouses, improving efficiency, sustainability, and crop quality.

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Introduction

With the global population rising, the shift towards protected cultivation in greenhouses is not just a trend but a necessity. Water scarcity, nutrient-depleted soils, and pollution are significant challenges worldwide, and they are likely to worsen with the increasing global population (Magwaza et al., 2020). Greenhouse technology is a critical component of profitable and sustainable agricultural intensification practices. Its primary goal is to create an ideal environment for intensive production, protecting crops from adverse climate conditions and pest infestations. The role of greenhouse technology in modern agriculture is paramount, as it significantly boosts crop yields and promises a bright future for agriculture. These systems offer a viable solution for ensuring food supply, a significant challenge for humanity in the twenty-first century (Aznar-Sanchez et al. 2020). Greenhouses are a primary cultivation system where the environment is artificially controlled to benefit plants (Jung et al.,

2022). By adjusting internal climate conditions such as temperature, humidity, light intensity, and CO_2 concentration, greenhouses ensure optimal plant growth, providing a reassuring economic benefit. This reassurance stems from the fact that greenhouse technology is a powerful tool in our arsenal to address the challenges of a growing population and climate change, ensuring a confident future for food production.

Greenhouses

A modern greenhouse is an enclosed space designed for growing fruits and vegetables. Its translucent outer shell, typically made of rigid polycarbonate plastic, glass panes, or polyethylene film, creates an environment that controls optimal plant growth. These structures are equipped with screening installations and cooling, heating, and lighting systems, all of which can be computer-controlled to create the perfect environment for plant growth. Greenhouses, available in various types, are versatile in cultivating multiple plants. They all feature large areas covered with transparent materials that allow sunlight to pass through while trapping heat. Their primary function is to create optimal conditions for the growth of plants and shield crops from pests and adverse weather conditions.

Greenhouses, through technology, regulate temperature, humidity, lighting, and other factors to establish an ideal environment for cultivation (Achour et al., 2021). This versatile farming method, with its potential to cultivate a wide range of plants, from vegetables to fruits to flowers, showcases the technology's adaptability and potential for diverse agricultural applications. It helps plants produce more, enhances quality, increases the value of produce, and significantly reduces loss using best practices, providing a reassuring economic benefit. Light has a positive effect on the quantity of yield and its quality. In greenhouse horticulture, light should be considered an essential component of overall farm management rather than a separate growth factor (Marcelis, 2006).

Cultivation in greenhouses

Cultivation in greenhouses is a method of farming that holds the potential to transform agriculture. It involves growing crops in a controlled environment, sheltered structures covered by transparent material. Greenhouses can control the humidity and temperature of the environment inside greenhouses, opening up a world of possibilities for agriculture. These permanent, climate-controlled, and enclosed structures are used year-round for cultivating or safeguarding delicate plants. Equipped with heating, cooling screening installations, and lighting, a computer can control modern greenhouses to create favorable conditions for plant growth. We can use different techniques to manage the growing conditions, including relative humidity, temperature, and vapor-pressure deficit, to develop an optimal environmental condition for cultivating a particular crop. The covering materials of the greenhouse should be chosen based on the greenhouse's location and yield type (Badji et al., 2022).

Greenhouse farming enables us to grow crops year-round, regardless of seasonal variations. The controlled atmosphere in greenhouses creates ideal conditions for plant growth, extends the season for growing, and ensures continuous and predictable food production. This reduces vulnerability to climatic interruptions, improving food security by allowing farmers to diversify their crops and meet market demands even during the off-season. In addition to providing sustainable and managed food production, greenhouse farming offers various income prospects. The rising global population, especially in developing countries, requires other alternatives for sustainable crop production. Cultivation in controlled environments using functional and durable greenhouse structures presents an option (Omobowale, 2020).

By taking a comprehensive approach to revenue generation, greenhouse farming allows for exploring several options while supporting local and sustainable agriculture. Whether through crop sales, value-added goods, or

educational activities, greenhouse farming can be a fulfilling and successful endeavor. Horticultural production inside the greenhouses is a highly effective method of intensive cultivation. Therefore, modern technologies and cultivation practices are crucial for production in a competitive environment.

Profitable greenhouse cultivation

Proper and optimal use of an intelligent greenhouse is essential, and if utilized correctly, it can produce excellent results. An intelligent greenhouse can optimize production and prevent diseases that endanger hundreds of plants. Implementing these methods has led to higher profitability for farmers than traditional open-field farming practices. Factors such as climate, topography, availability of irrigation water, soil quality, risk of flooding, air pollution, the potential for expansion, labor availability, communication infrastructure, and orientation all play a significant role in determining the suitability of a site for greenhouse research and production purposes (Ahuchaogu et al., 2022). The agricultural products dried in greenhouses are better quality than those dried in the open sun because they are protected from dust, rain, insects, birds, and animals (Sahdev et al., 2019). Climate change has increased extreme weather events such as heatwaves, droughts, and storms. These events have significantly impacted agriculture, leading to crop damage. Greenhouse cultivation offers a controlled environment that protects crops from external weather conditions and pests. It requires precise microclimate control (Sun and Chang, 2023).

The benefits of greenhouse

1. Greenhouses help protect crops from diseases, pests, and adverse weather conditions, which can lead to the production of high-quality crops.
2. Greenhouses take advantage of environmental conditions to optimize internal heat, so energy efficiency can be achieved by using greenhouses.
3. The greenhouse helps distribute light evenly over the entire surface by changing the direction of the sun's rays. This benefits all plants in the greenhouse while avoiding direct exposure to the sun's rays. So, there is good light distribution inside the greenhouse.
4. Because greenhouses are enclosed, pests find them difficult to enter, so ultimately, protection against diseases, pests, and other vermin.
5. Greenhouses allow for controlling and maintaining optimal growing conditions by adjusting temperature, humidity, lighting, and other factors.
6. Greenhouse environmental control allows for off-season production, leading to better sale prices and a continuous product supply.
7. Greenhouses can be ventilated quickly through zenithal or side windows.
8. Increased production. Greenhouses can intensify production by mitigating the impact of weather conditions, accelerating plant growth, and allowing for more crops on the surface.
9. We can take production in regions with adverse weather conditions.
10. Greenhouses enable multiple crop cycles per year and the growth of different plant species.
11. Optimization of other technologies to manage climate (heating, humidification, shade screens, energy conservation, etc.
12. Greenhouses can lead to higher yields per unit area, increasing farmers' profitability.
13. Greenhouses can reduce water usage and the requirement for pesticides and fertilizers.

Greenhouses allow the utilization of available resources. Greenhouse farming can result in two to three times as much profit per crop per square foot as open-field agriculture. This is because greenhouses allow you to utilize resources more efficiently, which can create less wastes more efficiently, which can create less waste.

Greenhouse farming can produce two to three times more profit per crop than field agriculture. Achieving optimal greenhouse microclimate conditions, implementing integrated pest management strategies, and utilizing an innovative closed-loop system with water recycling can substantially decrease plant diseases. This, in turn, reduces the need for agrochemicals and results in lower water and fertilizer consumption (Vox et al., 2010).

Advancements in greenhouse technology

Greenhouse technology is now significantly advanced. Innovative techniques and features are incorporated to improve productivity and efficiency. Modifications and advancements in greenhouse technology have led to solutions for optimal plant production in all seasons. This is achieved by altering internal growing factors in the greenhouse, such as humidity, temperature, CO_2 concentration, and light intensity.

Here are some notable advancements in greenhouse technology:

1. Many modern greenhouses use sustainable growing practices, such as water recycling, integrated pest management (IPM), and organic cultivation, to promote environmental stewardship and reduce reliance on synthetic inputs.
2. Modern greenhouses have advanced climate control systems that monitor and regulate temperature, humidity, ventilation, and CO_2 levels to ensure optimal growing conditions, resulting in healthier and more productive crops.
3. Greenhouses utilize supplemental lighting systems, such as LED grow lights, to give plants the necessary light spectrum for photosynthesis. These lighting solutions offer energy efficiency, customizable settings, and precise light intensity and duration control.
4. Greenhouses now use automated irrigation systems to deliver water precisely to the plants based on their specific needs, conserving water, preventing overwatering, and promoting efficient nutrient uptake.
5. New greenhouse structures have been developed, which include energy-efficient designs, such as double-glazed or multi-layered materials, to enhance insulation, reduce heat loss, and minimize energy consumption. Solar panels and renewable energy sources are commonly integrated to power greenhouse operations.

Addressing climate change

The pressing need to address climate change and shift towards a sustainable future has gained widespread global support. With extreme weather conditions, rising temperatures, and natural resource depletion, the urgency to adopt green solutions has become essential. Greenhouse technology enables faster, more efficient, and sustainable crop growth. Modern greenhouses are highly sustainable and advanced in water usage, allowing for a consistent year-round supply of local food. This makes them well-suited for meeting local food market demands and overcoming future challenges related to global food security. As greenhouse crop production becomes increasingly important, there is a focus on optimizing water-use efficiency and ensuring better product quality and safety control.

The "Green Revolution" article explores innovative solutions to accelerate the transition to green technologies and combat climate change. It highlights key areas such as energy storage technologies, renewable energy sources, electric mobility, sustainable agriculture, circular economy initiatives, intelligent cities, and climate finance. These solutions offer promising ways to create a greener and more sustainable world. By implementing these transformative measures and fostering collaboration among businesses, governments, and individuals, we

can pave the way for a brighter future for the planet and future generations. This collective effort unites us in a global movement towards sustainability.

Environmental degradation and climate change challenges necessitate immediate and innovative action. Fortunately, the transition to green technologies offers a range of solutions that can help us achieve a more prosperous and sustainable future. By embracing renewable energy, revolutionizing transportation, promoting sustainable agriculture, adopting circular economy practices, and investing in smart infrastructure, we can collectively work towards mitigating the impacts of climate change and preserving the planet for future generations. It requires collaboration among governments, businesses, and individuals to accelerate the transition and secure a brighter, greener future for all.

The management of greenhouse environments is tailored to specific regions and weather conditions. In dry climates, evaporative cooling and solar heating are recommended in arid and semi-arid areas. A shading system should also help to control high light intensity and temperatures. In tropical regions, natural ventilation is highly adequate for humidity inside and air treatment, especially for managing carbon dioxide levels and temperature. A commercial irrigation controller unit utilizing artificial intelligence analyses is needed to model and monitor the soil-plant-atmosphere (Nikolaou et al., 2019).

Modern agriculture and greenhouses

Greenhouse technology has transformed agriculture by creating a controlled environment for growing crops. Greenhouses are crucial in contemporary agriculture because they provide a controlled environment for growing crops. They protect plants from fluctuations due to season and extreme weather conditions. Farmers can extend the growing season by adjusting the climate within the greenhouse, increasing production levels throughout the year. This allows farmers to grow crops in other seasons, providing a reliable food supply.

Greenhouses are rising, thanks to information technology and innovative decision-support systems. Greenhouse farming can use intelligent agricultural technologies, such as remote monitoring systems, precision agriculture, and various IoT devices. Implementing new technologies can offer real-time data and insights on growth conditions, plant health, and resource usage, ultimately enhancing farmers' efficiency and decision-making. Farmers can automate processes, reduce labor costs, and improve operational performance by integrating intelligent technologies into greenhouse systems. Guo et al. (2024) reported that the greenhouse sector would be able to adapt and achieve the necessary transformation by adjusting the growing structure of greenhouse crops, adopting a reasonable multi-level growing mode, combining the growth of high fruit trees with low melon plants, improving the competitiveness of greenhouse products, and introducing new types of high-quality products. Greenhouse farming has numerous advantages, demonstrating its potential to revolutionize agriculture by increasing yield and promoting sustainability. Farmers can overcome the challenges of a growing population and climate change affecting food production with various innovations in greenhouse farming. Many solutions are available for optimizing greenhouse farming practices, allowing growers to make the most of this advanced approach. The new generation of greenhouses has evolved from simple, covered structures to advanced factories that optimize agricultural production at minimal cost. Greenhouse production systems decrease crop water requirements by 20% to 40% compared to open-field cultivation (Nikolaou et al., 2019). Today, intelligent systems enable greenhouses to grow crops faster, more efficiently, and sustainably in almost any environmental condition.

Vertical farming in greenhouses

The future of agriculture is a cause for concern and requires change. We need to find better ways to produce food for future generations. One significant advantage of greenhouse farming is optimizing growing space through vertical farming practices. Farmers can use the area available more efficiently and increase yield per square meter by employing vertical farming systems such as hydroponics and aeroponics. This offers an excellent solution to meet challenges and ensure food security for the future. In vertical farming, crops are grown in stacked layers indoors to maximize agricultural output in a small space. Plants are grown and stacked vertically to make the most available space. Multiple crops can be grown in layers, yielding higher crop yields in a small area.

This technology is designed to enhance plant growth by utilizing vertical grow lights, temperature regulators, and sensors to monitor growth. Vertical farming offers several advantages over traditional farming. It often involves controlled environment agriculture, necessitating artificial control of temperature, light, water, and humidity, all of which greenhouses can provide. Vertical farming in greenhouses leads to increased overall production and consistent year-round output. This method primarily benefits agriculture in urban areas with limited and costly land. Vertical farming in greenhouses yields 11 times more per unit area than traditional methods. Challenges include high initial expenses, expertise shortage, and the need for a controlled growing system. Despite this, vertical farming is gaining popularity for its reliable and sustainable food production (Oh and Lu, 2022).

The future of greenhouse technology: advancements and innovations

The future of greenhouse technology looks promising. Advancements in automation, artificial intelligence, and data analytics are transforming greenhouses into highly efficient and intelligent systems. These technologies enable real-time monitoring, precise control, predictive analytics, and autonomous operations, leading to increased productivity, optimized resource usage, and sustainability.

1. Climate control systems in modern greenhouses monitor and regulate temperature, humidity, ventilation, and CO2 levels to ensure optimal growing conditions, leading to healthier and more productive crops.
2. Artificial intelligence algorithms analyze sensor data, climate patterns, and crop characteristics to optimize greenhouse conditions. AI-driven control systems also autonomously adjust environmental factors, irrigation schedules, and lighting to ensure resource utilization and optimal growth.
3. Modern greenhouse systems have advanced sensors that monitor soil moisture, temperature, humidity, and nutrient levels. Real-time data is collected, which enables early detection of anomalies and stress factors affecting plant health. So we can make precise adjustments.
4. Robotic systems can perform tasks such as seed planting, pest control, and crop harvesting, which helps reduce the need for manual labor. Automated systems efficiently manage nutrients, lighting, and climate, saving human resources and boosting efficiency.
5. Collecting and analyzing big data within greenhouse operations enables optimization of crop growth cycles, predictive modeling, and identification of patterns, which helps to prove overall performance. Insights derived by analyzing data allow farmers to make informed decisions, which helps to enhance crop quality and improve yield.
6. Greenhouses use supplemental lighting systems, such as LED lights. These lighting solutions are energy-efficient, customizable, and allow precise control over light intensity and duration, providing plants with the specific light spectrum needed for photosynthesis.

7. Greenhouse technology is evolving to include vertical farming and hydroponic systems, which reduce land requirements, conserve water, and enable year-round production in urban areas.
8. Automated irrigation systems can be used in greenhouses, delivering water to the plants according to their specific needs. This helps prevent overwatering, conserve water, and efficiently promote nutrient uptake.
9. Studies on the performance of hydroponic systems for urban wastewater treatment have been increasing. This is mainly because of their potential to allow the decentralization of wastewater treatment and their capacity to provide continuous crop production. These facts may have a value-added advantage due to their positive impact on environmental protection and food security.
10. The greenhouse is a sustainable form of smart agricultural farming, requiring efficient, precise, and secure control and management of crop parameters. The Internet of Things (IoT) has introduced intelligent solutions to automate greenhouse farming parameters such as plant monitoring, internal atmosphere control, and irrigation (Farooq et al., 2022)

Challenges to the adoption of greenhouse technology

The main constraints in *greenhouse* farming are pests and diseases, inadequate water supply, and high input costs (Wayua, 2020). The high initial investment costs for green technology can hinder the widespread adoption of greenhouse technology and integration into existing systems and infrastructures. Regulatory hurdles, which vary by region, can impede the development and implementation of these technologies. Other challenges include insufficient infrastructure, policy and regulatory barriers, supply chain challenges, government support, business engagement, and public awareness and education. These challenges, though substantial, are being progressively addressed through technological advancements and societal shifts toward sustainability. Castro et al., 2019 demonstrated the importance of establishing transdisciplinary multi-actor work schemes to foster collaboration and research to transition to an agroecological model, ensuring competitiveness and value creation. Agriculture resource management is critical because greenhouse farming and agriculture-related activities account for approximately 10–29% of global greenhouse gas emissions. The persistent expansion of arable land to meet global food demand has led to unresolved high greenhouse gas emissions (Maraveas et al., 2023).

Case study

A case study of a profitable mid-tech greenhouse for the sustainable production of tomatoes, using a biofertilizer and a bio fungicide. This is a successful case study of mid-tech technology, suitable in middle-income countries like México. Using tomato as a model system, they tested if biocontrol and bio fertilization in mid-tech greenhouses can increase profits. This work considers middle-income countries' agriculture and the need for a multidisciplinary approach to offer cost-effective, sustainable alternatives to producers. This technology yielded up to 254 tons/ha of tomatoes, reducing 44–60% in water consumption, 25% in chemical nitrogen fertilization, and 28% in the cost unit of production. It also increased profits by ~45% in Mexican conventional greenhouse management. This case study has shown that it is possible to significantly increase earnings in mid-tech greenhouse tomato production by increasing productivity and crop quality and decreasing the use of water and agrochemicals through greenhouse automatization, crop management, and beneficial bacteria applied to crops (Serrano et al., 2022)

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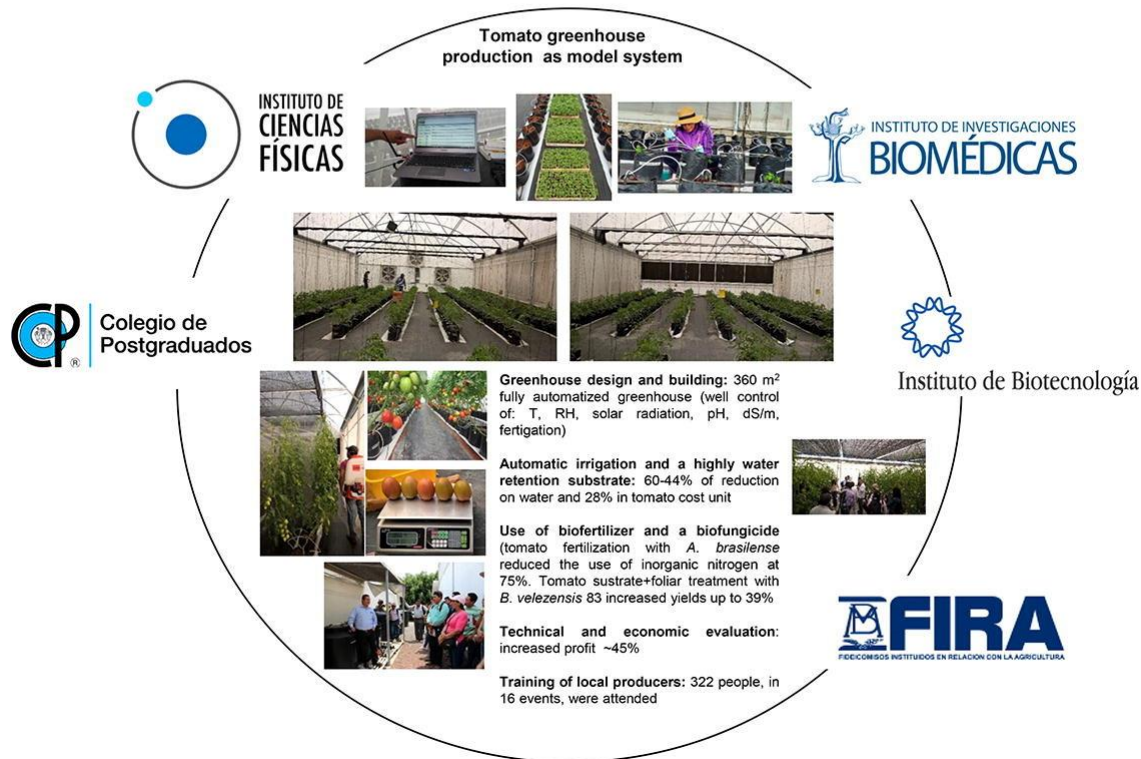
Source: Serreno, et al., 2022. Available at https: //doi.org/10.1016/j.ejbt.2022.06.003

Conclusion

Greenhouse technology has transformed modern agriculture by creating controlled environments that enhance plant growth and boost crop yields. Developments in climate control, automation, energy efficiency, and sustainable practices have resulted in benefits such as longer growing seasons, crop protection, higher productivity, and resource efficiency. As technology progresses, the future of greenhouse technology appears even more promising. Intelligent sensing, artificial intelligence, vertical farming, robotics, and data analytics will shape the next generation of greenhouses, improving efficiency, sustainability, and crop quality. Incorporating greenhouse technology into agricultural practices helps meet food security and sustainability demands. It also creates opportunities for innovation, entrepreneurship, and economic growth within the farming industry. By utilizing controlled environments, we can ensure the building of a more robust and productive agricultural sector for the future.

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