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Review Article

Climate-Smart Horticultural Practices: Building Resilience in a Changing Environment: A Scoping Review

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Abstract

Climate change disrupts weather patterns, intensifies water scarcity and exacerbates pest and disease pressures, posing a significant threat to horticultural production systems. This scoping review explores a range of climate-smart practices to enhance adaptation and resilience within the sector. Core practices like water-efficient irrigation, heat stress mitigation strategies, and adjustments to cropping patterns for altered rainfall are investigated. Integrated pest management is presented as a cornerstone for sustainable pest control. The review further explores the potential of precision agriculture, controlled-environment agriculture, and vertical farming to optimize resource use and mitigate climate risks. Beyond technical solutions, the review emphasizes continuous research and development for breeding climate-resistant varieties, refining existing practices, and exploring novel technologies. It advocates for an integrated approach, tailoring climate smart practices to specific contexts and socioeconomic considerations. Knowledge-sharing initiatives, training programs, economically viable technologies, and supportive government policies are identified as crucial for widespread adoption, particularly among smallholder farmers. The paper concludes with a call for collaboration among researchers, extension services, policymakers, and producers. By fostering knowledge dissemination, technology transfer, and financial incentives, stakeholders can empower farmers to adapt and thrive in a changing climate. Through collective action and unwavering commitment to innovation, the horticultural sector can ensure a secure and sustainable future for food production.

Keywords

Climate Change Adaptation, Climate-Smart Horticulture, Emerging Technologies, Climate-Resilient Crop Varieties, Precision Agriculture and Socioeconomic, Considerations

1. Introduction

Horticulture, encompassing the cultivation of fruits, vegetables, flowers, and ornamental plants, plays a critical role in global food security. It provides essential vitamins, minerals, and dietary fiber, promoting balanced diets and contributing significantly to human health, particularly in developing countries [11]. However, horticultural production faces a significant challenge: its vulnerability to climate change.

The Earth's climate is experiencing unprecedented change, characterized by an increase in global average temperatures, rising sea levels, and more frequent and intense extreme weather events [13]. For horticultural production, this translates to a multitude of threats. Droughts are becoming more common and severe, jeopardizing water availability – a crucial resource for plant growth [16].

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Heat stress events are also on the rise, pushing plants beyond their optimal temperature range and leading to reduced yields and fruit quality [28]. Additionally, altered rainfall patterns disrupt established irrigation schedules and can cause flooding or waterlogging in some regions [23].

In response to these escalating challenges, the concept of "climate-smart horticulture practices" has emerged. These practices aim to achieve a three-pronged approach: increasing productivity, enhancing adaptation to climate change, and mitigating greenhouse gas emissions associated with horticultural production [10]. By implementing climate-smart practices, horticultural producers can build resilience in the face of a changing climate, ensuring sustainable food production for future generations.

This review paper assesses the diverse range of climate-smart horticultural practices. Strategies for improving water use efficiency, optimizing soil health, selecting climate-resistant varieties, and harnessing technological advancements to create a more sustainable horticultural sector were explored. The review also discussed the role of integrated pest management and the importance of knowledge sharing and capacity building for farmers to adopt these practices effectively. Finally, the economic and environmental benefits associated with climate-smart horticulture were analyzed, and the future research and development direction in this critical field was explored.

1.1. The Significance of the Review

Climate change poses a dire threat to global food security, with horticultural production systems particularly vulnerable due to their dependence on specific weather patterns and water availability [38]. This review paper investigates the potential of climate-smart practices as a powerful strategy for adaptation and building resilience within the horticultural sector. By critically examining these practices and their associated benefits, this review aims to contribute to a more sustainable future for food production in the face of a changing climate.

1.2. Review Objective

The primary objective of this review is to provide a comprehensive overview of climate-smart horticultural practices. This includes exploring various practices for water management, heat stress mitigation, and adaptation to changing rainfall patterns. Additionally, the review examines the role of integrated pest management (IPM) and emerging technologies like precision agriculture, controlled environment agriculture, and vertical farming in enhancing resource efficiency and mitigating climate risks. Furthermore, the review emphasizes the importance of continuous research and development, integrated approaches, and socioeconomic considerations for successful implementation.

1.3. Review Methodology

This review employed a systematic approach to gather and analyze relevant scientific literature. Scholarly databases such as Scopus, Web of Science, and Google Scholar were used to search for peer-reviewed articles published within the past five years. The search terms included "climate-smart horticulture," "adaptation," "water management," "heat stress," "integrated pest management," "emerging technologies," and "socioeconomic considerations." The retrieved articles were then screened based on relevance, methodology, and quality of research. This process ensured the inclusion of credible and up-to-date information in the review.

1.4. Intended Audience

This review is intended for a broad audience interested in the future of sustainable food production in the face of climate change. The target audience includes:

1. Horticultural producers: This review can equip farmers with practical knowledge and strategies to adapt their practices to a changing climate and ensure long-term production sustainability.
2. Researchers: This review provides a comprehensive overview of current research efforts in climate-smart horticulture, highlighting potential areas for further investigation and development.
3. Extension service personnel: By understanding the benefits and challenges of climate-smart practices, extension workers can effectively guide and support farmers in adopting these approaches.
4. Policymakers: This review can inform policymakers in developing strategies and incentives to promote widespread adoption of climate-smart practices within the horticultural sector.

1.5. The Review as Input for Different Stakeholders

This review can serve as valuable input for various stakeholders within the horticultural sector:

1. Horticultural producers: By understanding the diverse climate-smart practices available and their potential benefits, farmers can make informed decisions about adopting these practices to enhance resilience and secure their livelihoods.
2. Researchers: The review highlights knowledge gaps and areas requiring further research and development for continuous improvement of climate-smart practices.
3. Extension service personnel: This review equips extension workers with the necessary knowledge to effectively communicate the benefits and challenges of climate-smart practices to farmers, facilitating their adoption.
4. Policymakers: The review can inform policymakers in

developing evidence-based policies that promote the adoption of climate-smart practices. This could include providing financial incentives for farmers, investing in research and development, and establishing market access for climate-smart produce.

By serving as a comprehensive resource for various stakeholders, this review can contribute significantly to the widespread adoption of climate-smart practices and ensure a more sustainable future for horticultural production in a changing climate.

2. Literature Review

2.1. Impacts of Climate Change on Horticulture

Climate change poses a significant threat to horticultural production due to its multifaceted impacts on various environmental factors crucial for plant growth and development [41].

2.1.1. Drought Stress

Droughts, characterized by prolonged periods of below-average precipitation, are becoming more frequent and severe due to climate change. This translates to reduced water availability, a critical resource for plant growth. As water stress intensifies, soil moisture levels decline, leading to increased evapotranspiration and ultimately wilting and reduced plant growth [40]. Furthermore, drought stress triggers various physiological responses in plants, including stomatal closure to conserve water, reduced photosynthesis, and impaired nutrient uptake [25]. These combined effects can significantly impact yield and fruit quality in horticultural crops.

2.1.2. Heat Stress

Rising global temperatures associated with climate change pose another major threat to horticulture. Heat stress occurs when ambient temperatures exceed a crop's optimal range, disrupting essential physiological processes. Extreme heat events can negatively impact pollination, a crucial stage in fruit set for many horticultural crops [28]. Additionally, high temperatures can lead to misshapen fruits, sunburns, and reduced overall yield [12]. Furthermore, heat stress can decrease the quality of fruits and vegetables by reducing their sugar content, increasing susceptibility to diseases, and accelerating post-harvest spoilage [28].

2.1.3. Altered Rainfall Patterns

Climate change also disrupts established rainfall patterns, leading to increased unpredictability in water availability for horticultural crops. Extreme precipitation events, including intense rainfall and short-duration downpours, can cause flooding in low-lying areas, damaging crops and infrastructure [23]. Conversely, prolonged periods with minimal to no rainfall exacerbate drought conditions, further stressing horticultural production. Additionally, intense rainfall can lead to soil erosion, washing away valuable nutrients and topsoil, ultimately reducing soil fertility and productivity [17].

2.1.4. Increased Pest and Disease Incidence

Climate change can also indirectly impact horticulture by creating favorable conditions for pests and pathogens. Rising temperatures and changes in humidity levels can alter the distribution and population dynamics of insect pests and disease-causing organisms [4]. Additionally, warmer temperatures can shorten the life cycle of certain pests, leading to increased generations and accelerated spread throughout the growing season [7]. These factors, coupled with potential stress-induced reductions in plant defenses, can lead to increased pest and disease outbreaks, causing significant yield losses in horticultural crops.

The combined effects of these climate change impacts present a significant challenge for horticultural production. However, by implementing climate-smart practices, producers can build resilience, adapt to these changing conditions, and ensure the sustainability of the sector.

2.2. Climate-Smart Horticultural Practices for Adaptation

In response to the challenges posed by climate change, a range of climate-smart horticultural practices have emerged. These practices aim to enhance adaptation, improve resilience, and ensure the sustainability of horticultural production in a changing climate.

2.2.1. Water Management Strategies

Effective water management is crucial for adapting to drought and erratic rainfall patterns. Several practices can help conserve water and optimize its utilization in horticultural production:

1. Rainwater harvesting techniques: Capturing and storing rainwater during periods of high precipitation can provide a valuable supplementary water source during dry periods. Simple techniques like installing rain barrels or constructing larger cisterns can be employed [10].
2. Efficient irrigation practices: Traditional flood irrigation methods can be wasteful, leading to high water losses through evaporation. Implementing efficient irrigation systems like drip irrigation or micro-irrigation can significantly improve water use efficiency by delivering water directly to the root zone of plants [18].
3. Drought-tolerant crop varieties and rootstock selection: Selecting crops and rootstocks with inherent drought tolerance can significantly improve resilience in water-scarce environments. These varieties have adaptations like deeper root systems that allow them to access water stored deeper in the soil profile [14].

4. Soil health improvement: Healthy soil with good water holding capacity can act as a buffer during dry periods. Practices like mulching with organic materials and cover cropping can improve soil structure, increase water infiltration, and reduce evaporation [6].

2.2.2. Heat Stress Management

Horticultural production can be adapted to rising temperatures through various strategies:

1. Selection of heat-tolerant varieties and cultivars: Research efforts are continuously developing new crop varieties with improved heat tolerance. Selecting these varieties can help minimize yield losses and ensure fruit quality under hotter conditions [12].
2. Shade netting and cooling techniques: Utilizing shade netting strategically can reduce the amount of direct sunlight reaching plants, mitigating heat stress and preventing sunburn on fruits and vegetables [26]. Additionally, evaporative cooling techniques like misting systems can create a cooler microclimate around plants during peak heat periods.
3. Planting schedules and crop rotations: Adjusting planting schedules to avoid peak heat periods can be beneficial. For example, planting crops earlier or later in the season depending on the local climate can help them escape the hottest part of the year [23]. Implementing crop rotations with heat-tolerant cover crops can also provide temporary shade and improve soil health.

2.2.3. Managing Altered Rainfall Patterns

Several practices can help adapt to unpredictable and extreme rainfall events:

1. Improved drainage systems: Ensuring well-maintained and effective drainage systems in fields is crucial for preventing waterlogging and root rot damage during heavy rains [10].
2. Raised bed cultivation: Constructing raised beds can elevate crops above the ground level, improving drainage and preventing waterlogging in areas prone to flooding [18].
3. Flood-tolerant crop varieties: Selecting crop varieties with tolerance to flooding can help minimize yield losses in areas prone to inundation. These varieties may have adaptations such as elongated stems or the ability to germinate underwater [10].

These climate-smart practices offer a diverse toolkit for horticultural producers to adapt to the changing climate. By implementing these strategies in a context-specific manner, producers can enhance resilience, optimize resource utilization, and ensure the long-term sustainability of their production systems.

2.2.4. Integrated Pest Management (IPM)

The emergence of pest and disease threats due to climate change necessitates effective management strategies. Integrated Pest Management (IPM) offers a sustainable approach for horticultural producers to control pest populations while minimizing environmental impact [37]. IPM utilizes a combination of methods to achieve long-term pest suppression:

1. Utilizing natural predators and biological control agents: Encouraging and promoting populations of beneficial insects and organisms that naturally prey on pests can be a powerful tool within IPM. This can involve creating suitable habitats for these beneficial insects or introducing commercially available bio-control agents [10].
2. Utilizing resistant varieties and optimizing application of pesticides: Selecting crop varieties with inherent resistance to specific pests and diseases can significantly reduce reliance on chemical control methods. However, pest populations can evolve and overcome resistance over time. IPM emphasizes using pesticides judiciously, only when necessary, and applying them in a targeted manner to minimize environmental impact and prevent the development of resistance [18].
3. Monitoring and forecasting pest outbreaks based on climate data: Climate data can be a valuable tool for predicting pest outbreaks. By monitoring weather patterns and correlating them with historical pest trends, producers can anticipate potential problems and implement preventative measures before populations escalate [8]. This approach can optimize resource allocation and reduce reliance on reactive pest control strategies.

2.2.5. Additional Climate-Smart Practices

Beyond the specific practices mentioned above, several other strategies can contribute to climate-smart horticulture:

1. Precision agriculture: Utilizing technologies like sensors and data analysis allows for targeted resource application, optimizing water and fertilizer use based on real-time needs [19].
2. Post-harvest management practices: Implementing proper storage and handling techniques can minimize post-harvest losses, reducing overall food waste and enhancing resource efficiency [5].
3. Climate-informed variety selection: Selecting crop varieties with shorter growing seasons or improved drought tolerance can help producers adapt to changing climatic conditions and maintain crop yields [39].

These additional practices, when combined with the core strategies discussed previously, create a holistic approach to climate-smart horticulture.

3. Emerging Technologies and Innovations

Beyond established climate-smart practices, advancements in technology offer exciting possibilities for enhancing horticultural production in a changing climate. These innovations can improve resource efficiency, optimize production systems, and contribute to greater resilience in the face of climate challenges [36].

3.1. Precision Agriculture

Precision agriculture (PA) utilizes a suite of technologies to collect real-time data on various aspects of the horticultural environment. This data, often gathered through sensors deployed in fields or greenhouses, can include soil moisture levels, air temperature, nutrient availability, and plant health indicators [35]. Advanced data analysis tools then translate this raw data into actionable insights for producers.

1. Optimizing Resource Use: PA empowers producers to make data-driven decisions regarding resource utilization. By monitoring soil moisture, for instance, producers can implement irrigation strategies that precisely match crop needs, minimizing water waste and optimizing water use efficiency [19].
2. Adapting to Changing Weather Conditions: PA data can be used to monitor weather forecasts and adjust management practices accordingly. Early warnings of frost events, for example, can trigger the activation of frost protection measures, safeguarding crops from damage [21].

3.2. Controlled Environment Agriculture (CEA)

Controlled environment agriculture (CEA) encompasses a range of technologies that enable precise manipulation of the growing environment within greenhouses or indoor facilities [32]. This allows for year-round production regardless of external weather conditions and minimizes reliance on traditional climate control methods.

1. Managing Temperature, Humidity, and Light: CEA systems can regulate temperature, humidity, and light levels within the growing space. This creates optimal conditions for specific crops, promoting consistent growth and reducing stress caused by external climate fluctuations [15].
2. Reduced Dependence on Climate: By decoupling production from external climate conditions, CEA offers a buffer against the uncertainties of weather patterns associated with climate change. This can contribute to improved yield stability and reduced crop losses [31].

3.3. Vertical Farming

Vertical farming utilizes stacked layers for crop production, maximizing space utilization in urban or peri-urban environments. This innovative approach offers several potential benefits in the context of climate-smart horticulture:

1. Increased Resource Efficiency: Vertical farms can significantly reduce water usage through closed-loop hydroponic systems or aeroponic techniques. Additionally, they can optimize nutrient delivery and minimize fertilizer runoff [9].
2. Urban Food Production: Vertical farms can establish local food production hubs within urban areas, reducing transportation costs and associated environmental impacts. This approach can contribute to more sustainable and resilient food systems, particularly in densely populated regions.

The integration of these emerging technologies into horticultural practices holds significant promise for a future of climate-smart food production. However, it is crucial to acknowledge potential challenges like the initial investment costs associated with implementing PA and CEA systems, or the energy requirements of certain vertical farming technologies. Continued research and development efforts focused on cost reduction, energy efficiency, and broader accessibility will be critical for maximizing the impact of these innovations.

3.4. Socioeconomic Considerations and Capacity Building

The successful implementation of climate-smart horticultural practices requires addressing not only technical aspects but also socioeconomic considerations. Building capacity, fostering knowledge sharing, and ensuring economic viability are crucial for widespread adoption, particularly among smallholder farmers [34].

3.5. Knowledge Sharing and Training

The effectiveness of climate-smart practices hinges on the knowledge and skills of those implementing them [33]. Effective knowledge sharing and training programs are essential for empowering farmers to understand and utilize these approaches.

1. Tailored Training Programs: Training programs should be designed to be context-specific, considering local needs, existing knowledge base, and preferred learning styles of farmers [20]. Information dissemination can be delivered through various channels, including field demonstrations, workshops, and farmer-to-farmer learning exchanges.
2. Capacity Building for Long-Term Sustainability: Training programs should not be limited to one-off sessions. Building long-term capacity involves ongoing support mechanisms, such as farmer advisory services and hotlines, to address emerging challenges and ensure continuous learning [3].

3.6. Extension Services and Government Policies

Extension services play a critical role in bridging the gap between research and practical application. Effective extension services can:

1. Disseminate Knowledge and Best Practices: Extension agents can serve as a vital link between research institutions and farmers, disseminating information on climate-smart practices and promoting their adoption [1].
2. Support Policy Implementation: Extension services can play a crucial role in assisting farmers in navigating and complying with government policies that incentivize climate-smart practices [30].

Government policies also play a significant role in shaping the landscape for climate-smart horticulture. Supportive policies can include:

1. Subsidies and Financial Incentives: Offering financial assistance for purchasing climate-smart technologies or implementing specific practices can encourage wider adoption, particularly among resource-constrained farmers [24].
2. Market Access and Value Chains: Policies promoting the development of markets for climate-smart produce can incentivize farmers and create a premium for sustainable practices [2].

3.7. Economic Viability and Affordability

While climate-smart practices offer numerous benefits, the economic viability and affordability of these technologies are crucial considerations, particularly for smallholder farmers.

1. Cost-Benefit Analysis: The economic viability of different practices needs to be carefully evaluated, considering not only the initial investment costs but also the long-term benefits like increased yields, reduced water use, and improved resource efficiency [22].
2. Scaling Up Affordable Solutions: Research and development efforts should focus on creating cost-effective and easily adaptable climate-smart technologies suitable for smallholder farmers' resource limitations [27].

By addressing these socioeconomic considerations, stakeholders can create an enabling environment for the widespread adoption of climate-smart practices. Effective knowledge sharing, robust extension services, supportive policies, and economically viable technologies are all essential components for building resilience and fostering a sustainable future for horticulture in the face of climate change [29].

4. Conclusion

Climate change presents a significant threat to horticultural production systems, disrupting weather patterns, increasing water scarcity, and exacerbating pest and disease pressures. However, the adoption of climate-smart practices offers a powerful pathway for adaptation and building resilience. These practices encompass a diverse range of strategies, including water management techniques for optimizing water use, heat stress management approaches to mitigate the negative impacts of rising temperatures, and adjustments to cropping practices to adapt to changing rainfall patterns. Integrated pest management (IPM) plays a crucial role by promoting sustainable pest control methods, while emerging technologies like precision agriculture, controlled environment agriculture, and vertical farming hold immense potential for further optimizing resource use and mitigating climate risks.

The successful implementation of climate-smart practices hinges not only on the technical aspects but also on continuous research and development. Ongoing efforts are essential to develop climate-resilient crop varieties with improved tolerance to drought, heat, and disease. Additionally, refining existing practices and exploring new technologies are crucial for ensuring long-term effectiveness under evolving climate scenarios.

5. Recommendations

For climate-smart horticultural practices to achieve widespread adoption and maximize their impact, an integrated approach is necessary. This approach should combine various practices, tailoring strategies to specific regional contexts and challenges. Integrating water management techniques with heat stress management strategies or combining IPM with the adoption of climate-resilient varieties can create a more robust and holistic approach to adaptation.

Furthermore, addressing socioeconomic considerations is paramount. Effective knowledge sharing programs, capacity building initiatives for farmers, and the development of economically viable technologies are crucial for promoting adoption, particularly among resource-constrained smallholder farmers. Supportive government policies, such as subsidies for implementing climate-smart practices and market access for climate-smart produce, can further incentivize widespread adoption.

Finally, a call to action is imperative. Climate change demands immediate and collective action from all stakeholders within the horticultural sector. Collaboration between researchers, extension services, policymakers, and producers is essential. By creating a supportive environment for knowledge sharing, technology dissemination, and financial incentives, stakeholders can empower farmers to adapt and thrive in a changing climate. Through unwavering commitment to continuous innovation and widespread adoption of climate-smart practices, the horticultural sector can not only survive but flourish in the face of climate challenges, ensuring a secure and sustainable future for food production.

Abbreviations

CSPs	Climate-smart Practices
CEA	Controlled-environment Agriculture
FAO	Food and Agriculture Organization of the United Nations

IPCC Intergovernmental Panel on Climate Change
IPM Integrated Pest Management

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Conflicts of Interest

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