Berhan International Research Journal of Science and Humanities (BIRJSH), 2023, 7(1), 152–169

Journal homepage: www.journals.dbu.et *ISSN: 2414-2794*

Sustainable Insect Pest and Disease Management in Vertical Farming

Wondimagegn Atilaw

Department of Horticulture, College of Agriculture and Natural Resource Sciences, Debre Berhan University, P.O.Box: 445, Debre Berhan, Ethiopia

DOI: https://doi.org/10.61593/DBU.BIRJSH.01.07.09

Abstract

The global population is estimated to reach 9.7 billion by 2050, creating substantial pressures on the agri-food industry amid climate change challenges. To address these demands and ensure future food security, there is a growing focus on alternative food production systems, including vertical farming. This innovative approach aims to enhance crop yield per land area by transitioning from traditional horizontal cultivation to vertical cultivation, integrating advanced technologies within controlled environment facilities or glasshouses. Despite the increasing adoption of vertical farming, there is a notable lack of comprehensive scientific exploration in this field, particularly regarding crucial aspects such as pest and disease management. This is especially pertinent due to the unique challenges introduced by the innovative methods of vertical farming, impacting crop health and produce quality. Additionally, the diverse range of horticultural fresh produce species involved in vertical farming necessitates the management of a wide array of pests and diseases. This discussion sheds light on the considerations and opportunities for effectively managing pests and diseases in the prevailing stacked horizontal vertical farming systems, which utilize vertically stacked configurations of horizontal growth beds in controlled environment facilities or glasshouses.

Keywords: Hydroponics, Pest control, Plant pathogens, Sustainability, Vertical farming,

*Corresponding author email: atilaw12@gmail.com

Article information: Received 09 October 2023; Revised 27 December 2023; Accepted 30 December 2023

Introduction

By 2050, the global population is projected to reach 9.7 billion, placing significant demands on the agri-food industry in light of climate change (United Nations, 2015). This necessitates the creation of higher-yield, resource-efficient practices to enhance sustainability (Abou-Hussein, 2012; Al-Chalabi, 2015; Godfray et al., 2010; Rosenzweig et al., 2014; Wheeler and Von Braun, 2013). To ensure future global food security, research is focused on alternative food production systems, including vertical farming. This approach encompasses various farming methods aimed at increasing crop yield per land area by shifting the focus from spreading out horizontally to cultivating vertically. Despite being considered a recent development, concepts of such methods date back to the early 20th century (Al-Kodmany, 2018). In its current form, vertical farming integrates cutting-edge technology and is commonly practiced within controlled environment facilities or glasshouses with glass or plastic outer walls.

The realm of vertical farming encompasses a variety of approaches, including green walls and cultivation around vertically-oriented cylinders. However, the predominant method involves the utilization of stacked horizontal beds for soil-based or soil-free cultivation (Beacham et al., 2019). This sector has experienced rapid growth, attracting significant interest and investment from various stakeholders due to its perceived potential as the future of food production, particularly in urban settings.

Despite the increasing adoption of vertical farming systems, they have yet to undergo comprehensive scientific examination (Al-Chalabi, 2015; Beacham et al., 2019; Eigenbrod and Gruda, 2015; Mok et al., 2014). As an emerging agricultural practice that employs innovative production systems, vertical farming introduces new considerations in managing traditional issues such as disease and pest control. These factors, which are caused by herbivory and the transmission of plant pathogens, are of significant concern (Whitfield et al., 2015). While some parallels may exist with conventional protected horticultural systems, the unique methods of vertical farming may introduce new challenges related to crop health and quality produce. Furthermore, the wide array of horticultural fresh produce species involved in crop selection for vertical farming necessitates the management of a diverse range of pests and diseases (Beacham et al., 2019). This discussion focuses on the considerations and opportunities for managing pests and diseases in stacked horizontal vertical farming systems, which utilize vertically stacked configurations of horizontal growth beds in glasshouses or controlled environment facilities and are the prevailing system utilized globally (Beacham et al., 2019).

Mitigating Pests in Vertical Farming

Advocates of vertical farming argue that these systems, within protective structures, can prevent access by insects, but complete prevention is unrealistic (Despommier, 2013). Various introduction mechanisms and challenges during produce removal require meticulous air filter and airlock-based systems, employee training, strict phytosanitation protocols, and regular maintenance of structures. Implementing monitoring systems for early detection and proper ventilation designs can further minimize pest entry (Goodman and Minner, 2019). In addition to the aforementioned challenges, the small size of microorganisms and pests facilitates their access into even the most well-maintained 'pest-proof' protected growing systems (Hussey et al., 1969). These factors highlight the need for comprehensive measures beyond structural boundaries (Brechner and de Villiers, 2013). Adequate training of employees and strict adherence to phytosanitation protocols emerge as crucial components in minimizing the risk of introducing pests and diseases into protected horticulture systems. Moreover, regular maintenance of glasshouse and controlled environment structures, including thorough cleaning and inspection, is outlined as a necessary preventive measure (Bhuyan et al., 2023). To further enhance pest management in vertical farming, ongoing research and development focused on improving pest prevention and control mechanisms is deemed essential. Properly designed and maintained ventilation systems and doorways are highlighted as critical components in minimizing the risk of pest and pathogen entry in both glasshouses and controlled environment facilities (Hussey et al., 1969). Achieving an optimal balance between pest control measures and efficient produce removal processes is crucial in ensuring the effectiveness of these systems. Continuous improvement of protective measures and standards for pest and disease management in vertical farming is stressed as vital for reducing economic losses and ensuring the production of high-quality crops within these environments.

Mitigating Disease in Vertical Farming

While vertical farming structures can restrict the entry of diseases, complete prevention is also impractical (Smit et al., 1996). Disease and pathogen access can occur through various means and require continuous improvement through research, best practices, and ongoing assessment of disease management protocols. It is essential to recognize that the threat of disease cannot be entirely eradicated within vertical farming facilities, despite the stringent containment measures in place (Orozco et al., 2008). Continuous monitoring and adaptation of disease management strategies are imperative to address emerging threats and maintain a healthy growing environment. Effective disease management protocols are fundamental in safeguarding crop health and maximizing productivity within vertical farming systems (Boeing et al., 2012). Investing in research and innovation to develop new disease-resistant crop varieties can significantly contribute to disease prevention in vertical farming (Lehmann, 2010). The integration of advanced technologies, such as precision agriculture and data-driven monitoring, can enhance disease surveillance and response capabilities in vertical farming settings (Lenzi et al., 2021). Proactive engagement with regulatory agencies and adherence to industry guidelines are essential in upholding rigorous biosecurity standards to minimize the risk of disease incursions. Implementing robust sanitation practices and strict hygiene protocols throughout the vertical farming facility is crucial to prevent the spread of diseases among crops. Effective communication and coordination among staff members are essential for timely and coordinated responses to potential disease outbreaks in vertical farming environments. Developing contingency plans that outline specific steps for isolating and addressing disease incidents is pivotal in mitigating the impact on overall productivity. Regular assessment and refinement of disease management protocols based on observed outcomes and industry advancements are crucial for sustaining effective disease control in vertical farming (Jarvis and Jarvis, 1992).

Environmental impact on pests and diseases management in vertical farming

The growth conditions within vertical farming systems pose specific challenges for managing pests and diseases. Air circulation within these systems, essential for maintaining uniform growth conditions, can inadvertently aid the spread of pests and diseases such as plant pathogenic fungi, including grey mold (*Botrytis cinerea*), and arthropod pests like the two-spotted spider mite (*Tetranychus urticae*) (Li and LaMondia, 2010). Residual spatial heterogeneity within controlled environment systems can lead to a portion of the crop experiencing sub-optimal environmental conditions, affecting the susceptibility of plants to various pathogens. The high humidity levels in the restricted airspace between shelves may provide conducive conditions for disease development, which increases the activity of insects and could lead to increased pest damage (Yang et al., 2023).

Condensation on the lower surfaces of vertically stacked cultivation layers may contribute to the dissemination of diseases through the dispersal of fungal spores. The presence of water droplets descending between levels in vertical farming setups, whether due to condensation or irrigation, could serve as a conduit for facilitating the transmission of diseases. The influence of gravity could result in the transfer of insects or fungal spores from higher to lower shelves, thereby promoting the propagation of infections or damage from upper to lower tiers (Butterworth and McCartney, 1991).

Furthermore, settlement of spray droplets under the influence of gravity could lead to the accumulation of higher levels of pesticide on lower levels, potentially exceeding regulatory thresholds, increased treatment intervals prior to harvest, or phytotoxicity (Carotti et al., 2023). The specific growth conditions in vertical farming systems, such as limited space and high-density planting, can exacerbate the spread of pests and diseases. The proximity of plants within the vertical farming setup can facilitate the rapid spread of diseases, especially in cases of high humidity levels known to favor pathogen development (Fuller et al., 2008). Furthermore, the controlled environment and restrictive access limit the natural biocontrol or predator-prey relationships, potentially facilitating pest outbreaks (Santini et al., 2021). Limited space for maneuvering and inspection can make early pest or disease detection and mitigation more challenging, allowing infestations to gain a foothold before being noticed. The vertical stacking of crops creates environmental niches that can provide favorable conditions for pest and disease development, especially if not adequately managed (Atkinson and Urwin, 2012). The presence of a continuous food and habitat source due to the proximity of multiple tiers can lead to a quicker buildup of pest populations. The denser canopy within vertical farming systems can create microclimates that favor various pests, such as aphids or mites, due to the protection and increased humidity levels (Takeshima and Joshi, 2019).

It is essential to consider the implications of gravity on the management of pesticides and their potential adverse effects. The effects of gravity on pesticide distribution within vertically stacked systems can lead to uneven pesticide concentration, potentially causing phytotoxicity or exceeding regulatory limits for pesticide residue (Bostock et al., 2014; Brownbridge, 1995). Moreover, the increased treatment intervals prior to harvest necessitated by the accumulation of pesticides on lower levels can pose logistical challenges and impact harvest schedules. Proper application methods and strategic placement of pesticide applicators are crucial to mitigate the adverse effects of gravity on pesticide distribution. Implementing precision application techniques and devising strategies to account for the influence of gravity are essential to ensure uniform and effective pesticide coverage while minimizing environmental and phytotoxic risks. Well-designed and monitored application systems, considering the effects of gravity, can contribute to effective pest and disease management within vertical farming systems (Suzuki et al., 2014).

Insect movement and biocontrol challenges in vertical farming

In vertical farming systems, the movement of insects and the utilization of biocontrol measures present unique considerations related to the spatial arrangement and level separation. Flightless pests may encounter challenges in moving across different growth levels due to physical barriers, potentially hindering their ability to infest the entire crop. However, this separation could also pose difficulties for flightless biocontrol agents, such as the predatory mite *Phytoseiulus persimilis*, which may struggle to effectively move between levels within the vertical farm system (Frank, 2010). Consequently, a higher quantity of biocontrol agents may be required to address pest issues in each level, leading to increased costs compared to traditional growing systems, where a single treatment may suffice for the entire area (Symondson et al., 2002).

The need for separate treatments for each level in vertical farming systems could result in challenges related to cost-effectiveness and resource allocation, as added quantities of biocontrol agents may be necessary. Implementing "bridges" or connectors between growing levels could potentially facilitate the movement of biocontrol agents, reducing the need for excessive quantities of agents on each level. However, the implementation of such structures presents the risk of providing pathways for pests to traverse between levels, potentially undermining pest management efforts (Frank, 2010).

Careful consideration of the trade-offs involved in facilitating biocontrol agent movement between levels is necessary to navigate the challenges associated with pest management in vertical farming systems (Stacey, 1977). Balancing the need for effective pest management with the potential risks of creating pathways for pest movement through bridging structures is crucial for devising successful biocontrol strategies. Moreover, the integration of biocontrol measures in vertical farming systems entails the development of innovative and site-specific solutions to optimize the movement and efficacy of biocontrol agents while mitigating the potential downsides associated with structural modifications. Strategic planning and ongoing monitoring are essential to ensure that biocontrol measures are effectively deployed while minimizing the risks associated with pest movement facilitated by structural modifications (Loreau et al., 2001).

In the case of biocontrol agents capable of flight, the controlled environment of vertical farming offers a significant advantage as released insects remain within the structure and cannot disperse elsewhere (Paulitz and Bélanger, 2001). This partly explains the higher adoption of biocontrol in conventional horizontal-protected crops compared to outdoor crops (Paulitz and Bélanger, 2001). It is anticipated that biocontrol will play a crucial role in pest management within vertical farming systems. These systems may also accommodate structural features such as banker plants, which can be utilized to support populations of biocontrol agents (Frank, 2010; Paulitz and Bélanger, 2001)

Managing disease risks in hydroponic vertical farming

In vertical farming, the utilization of hydroponic growing systems introduces specific considerations for the management of diseases, requiring careful attention to potential microbial proliferation and the establishment of pathogenic species within the closed-loop environment (Pascual et al., 2018). Research findings have demonstrated that recirculating hydroponic systems can serve as a suitable habitat for various microorganisms, including detrimental fungi like Pythium, subsequently fostering conducive conditions for their proliferation and dissemination (Vanachter et al., 1982).

Despite the favorable environment for pathogen growth, the microbial content and diversity within the hydroponic system may not be adequate to effectively outcompete the detrimental species, potentially leading to heightened disease susceptibility (Zinnen, 1988). Consequently, maintaining rigorous control over the sanitation and microbiome of the hydroponic system is imperative to mitigate the development and spread of diseases. The nutrient film technique (NFT) systems, characterized by a relatively small volume of nutrient solution, afford greater ease in draining, flushing, and cleaning in response to disease occurrences, contributing to enhanced disease management within the hydroponic environment (Hanan, 2017). Addressing the challenges associated with disease management in hydroponic systems entails the application of water treatment methodologies such as UV irradiation, ozone, ultrafiltration, or heat treatment to effectively cleanse the hydroponic solution, thereby potentially reducing the prevalence of diseases (Jarvis and Jarvis, 1992; Vanachter et al., 1982).

While these disease management concerns are intrinsic to hydroponic cultivation, they may be further complicated by the scale and intricacy of the hydroponic systems indispensable within certain vertical farming configurations, necessitating comprehensive disease management strategies tailored to the specific context of multi-level vertical farming units. Notably, multi-level vertical farming systems hold the potential to segregate the nutrient solution flow to and from each level, thereby confining any nutrient solution-associated disease outbreaks to a single level, facilitating targeted disease mitigation and management efforts within the vertical farm (Vanachter et al., 1982).

Moreover, the controlled environment and isolated nature of hydroponic systems within vertical farming units offer the opportunity to introduce and incorporate plant protection products or biostimulants into the hydroponic growing environment, serving as adjunct measures to bolster pest and disease control and augment overall crop health and resilience. Adapting and integrating holistic disease management approaches within vertical farming hydroponic systems are essential to mitigate disease risks and ensure the sustained productivity and health of crops cultivated within the unique vertical farming setting.

Effects on semio-chemical communication in vertical farming

The interactions between organisms involve the perception of various types of information from their environment, including chemical compounds known as semiochemicals. Semiochemicals serve diverse functions, from mate location to predator avoidance (Herrmann, 2010). In integrated pest management (IPM), synthetic versions of semiochemicals are often used for pest monitoring, trapping, or mating disruption (Heuskin et al., 2011). It is suggested that vertical farming units may be suitable for mating disruption due to the protected environment hindering the infiltration of mated females from outside the treated area. The release rates of synthetic semiochemicals are influenced by environmental conditions (Torr et al., 1997), which could be altered in vertical farming systems with different temperature, humidity, or airflow patterns. The controlled, less windy conditions of indoor environments may improve prospects for the application of semiochemicals. On the other hand, a temperature gradient within a vertical farming system, if not carefully managed, may result in a gradient of semiochemical release and reduce its efficacy throughout the system. Increased humidity has been shown to decrease semiochemical release rates when formulated in alginate (Heuskin et al., 2012), while increased airflow reduces semiochemical concentration and efficacy, as concentration is important for olfactory recognition by invertebrates (Bruce et al., 2005). Therefore, to effectively deploy synthetic semiochemicals within vertical farming systems, it is crucial to consider the system design, environmental conditions, and the deployment of the semiochemical. There are opportunities to introduce semiochemical dispensers into the design of vertical farming structures.

Influence of lighting on pest and disease dynamics

The impact of lighting on vertical farming systems is a critical design consideration. Adequate illumination is essential not only for the optimal growth of crops but also influences their response to pests and pathogens. Crops grown in low-light conditions are often more susceptible to disease (Roberts and Paul, 2006). For instance, shade can promote infection by various pathogens, while full sun exposure can reduce herbivory in many species, though not universally (Roberts and Paul, 2006). To compensate for reduced light levels in lower growing levels, artificial lighting is commonly employed in vertical farming systems. High-efficiency LED lighting is frequently used due to its low energy consumption, customizable output spectrum, and minimal heat emission, which allows for close placement to the crops (Massa et al., 2008). However, it's important to note that LED illumination wavelength can impact insect behavior and pathogen growth, potentially altering pest and disease management approaches (Johansen et al., 2011; Paulitz and Bélanger, 2001).

Moreover, light quality has been found to influence disease development from viral, fungal, and bacterial sources. The spectral composition of LED light can impact disease development in fungi, with different wavelengths affecting sporulation and germ tube growth. For example, near UV light can induce sporulation, while blue light can inhibit it in certain fungi (Peterson et al., 1988). Overall, the choice of artificial illumination spectrum for vertical farming systems needs to consider not only the crop's needs but also the potential implications for pest and pathogen behavior. This includes influencing leaf physical properties, chemical content, and host defense responses, highlighting the need for a comprehensive approach to lighting design in vertical farming systems.

Plant density in vertical farming

In vertical farming, the primary objective is to maximize crop yield within the constraints of limited land area, necessitating strategic consideration of plant spacing and density to achieve this goal (Carotti et al., 2023). The arrangement and density of plants play a pivotal role in shaping the microclimate, thereby influencing pest and disease control and impacting disease (Touliatos et al., 2016). Effective management of plant density in vertical farming operations can significantly improve resource utilization and overall productivity, thereby contributing to the sustainability and efficiency of the system (Wicharuck et al., 2023). Adequate plant spacing facilitates the optimal flow of air and penetration of light, fostering healthy crop growth while reducing the risk of disease outbreaks. Furthermore, optimizing plant density supports the efficient use of water, nutrients, and other critical resources, thereby contributing directly to the economic viability of vertical farming (Burdon et al., 1989). The careful arrangement of plants in vertical farming systems can directly influence the microclimate, affecting factors such as temperature, humidity, and light availability, which are crucial for plant health and disease management (Burdon et al., 1989; Larsen et al., 2020). Strategic management of plant density can help mitigate potential disease risks by improving air circulation and light exposure, which are essential for maintaining optimal growing conditions and reducing the likelihood of disease outbreaks (Van Delden et al., 2021). Ensuring appropriate plant spacing is crucial for minimizing competition for resources such as water and nutrients, ultimately promoting efficient resource utilization and improved crop health in vertical farming systems. The interplay between plant spacing, microclimate, and resource utilization underscores the intricate balance needed to achieve high productivity and disease management in vertical farming operations. By carefully managing plant density, vertical farming systems can achieve improved overall production efficiency and resource utilization, contributing to the long-term sustainability and economic viability of the operation (Burdon et al., 1989).

Rotating vertical farming systems

Vertical farming systems employing rotating shelves aim to create a more consistent growth environment across different planting levels, mitigating variations in temperature and light exposure (Chow and Chithrameenal, 2015). Despite these advantages, the introduction of moving shelves brings new considerations for pest and disease management. Mechanical disturbance of plants and water droplets caused by the shelving movement could potentially disperse fungal spores, bacteria, and insects, while generating air currents that aid in pest movement and disease transmission (Gumble et al., 2015). The automated nature of these systems, however, presents an opportunity to reduce disease spread through human labor, provided that the design and maintenance of robotic management and harvesting systems are effectively executed. Substantial research is necessary to assess the efficacy of biocontrol methods and pollination in vertical farming systems, ensuring that these vital processes are adequately supported within this controlled environment (Massa et al., 2008). Proactive planning and specialized technology may be required to optimize pest and disease management in vertical farming systems with rotating shelves, acknowledging the unique challenges arising from their mechanized nature. Implementing comprehensive monitoring and control measures can help mitigate potential risks associated with the movement and operation of rotating shelves, safeguarding crop health and overall productivity in vertical farming setups. Considering these aspects is imperative to ensure that rotating shelf systems effectively balance the creation of uniform growth conditions with mitigating additional challenges related to pest and disease management. Regular assessment and fine-tuning of pest and disease management strategies in these systems are essential in maintaining their long-term viability and sustainability (Mir et al., 2022).

Scientific Examination and Future Research Directions

The current scientific examination of vertical farming systems has provided valuable insights into the potential and challenges of this innovative agricultural approach. Yet, there are notable knowledge gaps that necessitate further investigation and research. One aspect that is particularly salient is the need for a more comprehensive understanding of the dynamics within vertical farming systems, especially in relation to maximizing yield efficiency and addressing pest management. Future research endeavors could focus on conducting a comprehensive assessment of the environmental and energy implications of vertical farming systems. This could involve an in-depth analysis of factors such as energy consumption, resource utilization, and the overall ecological footprint of vertical farming operations. Understanding the environmental impact will be crucial for ensuring the long-term sustainability of vertical farming approaches. Investigating the dynamics of crop health and nutrient management within vertical farming systems presents a critical area for future research. This could encompass studies on optimizing nutrient delivery systems, assessing the impact of growing mediums on plant health, and developing innovative strategies to enhance the nutritional quality of crops cultivated in vertical farming environments.

Furthermore, future research endeavors should prioritize the development of advanced pest detection and management techniques tailored specifically to the unique challenges presented by vertical farming systems. This may involve the exploration of integrated pest management strategies, the utilization of cutting-edge sensors and monitoring technologies, and the development of predictive models to anticipate and mitigate pest outbreaks effectively. Investigating the integration of artificial intelligence (AI) and automation in vertical farming systems represents a promising area for future research. This could involve exploring the potential of AI algorithms for optimizing crop production, automating pest monitoring and management processes, and enhancing the overall operational efficiency of vertical farming facilities. Further research is warranted to optimize the design and layout of vertical farming systems to maximize yield efficiency while minimizing resource inputs. This may entail exploring innovative architectural designs, implementing efficient space utilization strategies, and evaluating the impact of different lighting and climate control systems on crop productivity.

Conflict of Interest

The authors declare that they have no known conflict of interest.

References

Abou-Hussein, S.D., (2012). Climate change and its impact on the productivity and quality of vegetable crops. J Appl Sci Res 8, 4359–4383.

Al-Chalabi, M., (2015). Vertical farming: Skyscraper sustainability? Sustain. Cities Soc. 18, 74–77.

Al-Kodmany, K., (2018). The vertical farm: A review of developments and implications for the vertical city. Buildings 8, 24.

Atkinson, N.J., Urwin, P.E., (2012). The interaction of plant biotic and abiotic stresses: from genes to the field. J. Exp. Bot. 63, 3523–3543.

Beacham, A.M., Vickers, L.H., Monaghan, J.M., (2019). Vertical farming: a summary of approaches to growing skywards. J. Hortic. Sci. Biotechnol. 94, 277–283.

Bhuyan, S., Laxman, T., Saikanth, D., Badekhan, A., (2023). Advanced Farming Technologies for Pollution Reduction and Increased Crop Productivity. Adv. Farming Technol. Scripown Publ. New Delhi India 194–214.

Boeing, H., Bechthold, A., Bub, A., Ellinger, S., Haller, D., Kroke, A., Leschik-Bonnet, E., Müller, M.J., Oberritter, H., Schulze, M., Stehle, P., Watzl, B., (2012). Critical review: vegetables and fruit in the prevention of chronic diseases. Eur. J. Nutr. 51, 637–663.

Bostock, R.M., Pye, M.F., Roubtsova, T.V., (2014). Predisposition in Plant Disease: Exploiting the Nexus in Abiotic and Biotic Stress Perception and Response. Annu. Rev. Phytopathol. 52, 517–549. https://doi.org/10.1146/annurev-phyto-081211-172902

Brechner, M., de Villiers, D., (2013). Cornell Controlled Environment Agriculture Hydroponic Spinach Production Handbook. Cornell Univ. CEA Program.

Brownbridge, M., (1995). Prospects for Mycopathogens in Thrips Management, in: Parker, B.L., Skinner, M., Lewis, T. (Eds.), Thrips Biology and Management. Springer US, Boston, MA, pp. 281–295. https://doi.org/10.1007/978-1-4899-1409-5_45

Bruce, T.J., Wadhams, L.J., Woodcock, C.M., (2005). Insect host location: a volatile situation. Trends Plant Sci. 10, 269–274.

Burdon, J.J., Jarosz, A.M., Kirby, G.C., (1989). Pattern and Patchiness in Plant-Pathogen Interactions—Causes and Consequences. Annu. Rev. Ecol. Syst. 20, 119–136.

Butterworth, J., McCartney, H.A., (1991). The dispersal of bacteria from leaf surfaces by water splash. J. Appl. Bacteriol. 71, 484–496. https://doi.org/10.1111/j.1365-2672.1991.tb03822.x

Carotti, L., Pistillo, A., Zauli, I., Meneghello, D., Martin, M., Pennisi, G., Gianquinto, G., Orsini, F., (2023). Improving water use efficiency in vertical farming: Effects of growing systems, far-red radiation and planting density on lettuce cultivation. Agric. Water Manag. 285, 108365.

Chow Kheong Keat, Chithrameenal Kannan, (2015). Development of a Cylindrical Hydroponics System for Vertical Farming. J. Agric. Sci. Technol. B 5.

Despommier, D., (2013). Farming up the city: The rise of urban vertical farms. Trends Biotechnol. 31, 388–389.

Eigenbrod, C., Gruda, N., (2015). Urban vegetable for food security in cities. A review. Agron. Sustain. Dev. 35, 483–498. https://doi.org/10.1007/s13593-014-0273-y

Frank, S.D., (2010). Biological control of arthropod pests using banker plant systems: Past progress and future directions. Biol. Control 52, 8–16.

Fuller, V.L., Lilley, C.J., Urwin, P.E., (2008). Nematode resistance. New Phytol. 180, 27–44. https://doi.org/10.1111/j.1469-8137.2008.02508.x

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food Security: The Challenge of Feeding 9 Billion People. Science 327, 812–818. https://doi.org/10.1126/science.1185383

Goodman, W., Minner, J., (2019). Will the urban agricultural revolution be vertical and soilless? A case study of controlled environment agriculture in New York City. Land Use Policy 83, 160–173.

Gumble, J., Berghage, R., Stearns, D., (2015). Production and Financial Analyses of the Rotating Living Wall, an Urban Agricultural System. J. Environ. Prot. 06, 1029.

Hanan, J.J., (2017). Greenhouses: Advanced technology for protected horticulture. CRC press.

Herrmann, A. (Ed.), (2010). The Chemistry and Biology of Volatiles, 1st ed. Wiley.

Heuskin, S., Lorge, S., Leroy, P., Haubruge, E., Béra, F., Brostaux, Y., Wathelet, J.-P., Lognay, G., (2012). A semiochemical slow-release formulation in a biological control approach to attract hoverflies. J. Environ. Ecol. 3.

Heuskin, S., Verheggen, F.J., Haubruge, E., Wathelet, J.-P., Lognay, G., (2011). The use of semiochemical slow-release devices in integrated pest management strategies. Base.

Hussey, N.W., Read, W.H., Hesling, J.J., (1969). The Pests of Protected Cultivation. The Biology and Control of Glasshouse and Mushroom Pests. Edward Arnold (Publishers) Ltd London.

Jarvis, W.R., Jarvis, W.R., (1992). Managing diseases in greenhouse crops.

Johansen, N.S., Vänninen, I., Pinto, D.M., Nissinen, A.I., Shipp, L., (2011). In the light of new greenhouse technologies: 2. Direct effects of artificial lighting on arthropods and integrated pest management in greenhouse crops. Ann. Appl. Biol. 159, 1–27.

Larsen, D.H., Woltering, E.J., Nicole, C.C., Marcelis, L.F., (2020. Response of basil growth and morphology to light intensity and spectrum in a vertical farm. Front. Plant Sci. 11, 597906.

Lehmann, S., (2010). The principles of green urbanism: Transforming the city for sustainability. Earthscan London.

Lenzi, A., Marvasi, M., Baldi, A., (2021). Agronomic practices to limit pre-and post-harvest contamination and proliferation of human pathogenic Enterobacteriaceae in vegetable produce. Food Control 119, 107486.

Li, D.-W., LaMondia, J., (2010). Airborne fungi associated with ornamental plant propagation in greenhouses. Aerobiologia 26, 15–28. https://doi.org/10.1007/s10453-009-9139-1

Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J.P., Hector, A., Hooper, D.U., Huston, M.A., Raffaelli, D., Schmid, B., Tilman, D., Wardle, D.A., (2001). Biodiversity and Ecosystem Functioning: Current Knowledge and Future Challenges. Science 294, 804–808. https://doi.org/10.1126/science.1064088

Massa, G.D., Kim, H.-H., Wheeler, R.M., Mitchell, C.A., (2008). Plant Productivity in Response to LED Lighting. HortScience 43, 1951–1956. https://doi.org/10.21273/HORTSCI.43.7.1951

Mir, M.S., Naikoo, N.B., Kanth, R.H., Bahar, F., Bhat, M.A., Nazir, A., Mahdi, S.S., Amin, Z., Singh, L., Raja, W., Saad, A., Bhat, T.A., Palmo, T., Ahngar, T.A., (2022). Vertical farming: The future of agriculture: A review.

Mok, H.-F., Williamson, V.G., Grove, J.R., Burry, K., Barker, S.F., Hamilton, A.J., (2014). Strawberry fields forever? Urban agriculture in developed countries: a review. Agron. Sustain. Dev. 34, 21–43. https://doi.org/10.1007/s13593-013-0156-7

Orozco, L., Rico-Romero, L., Escartin, E.F., (2008). Microbiological profile of greenhouses in a farm producing hydroponic tomatoes. J. Food Prot. 71, 60–65.

Pascual, M.P., Lorenzo, G.A., Gabriel, A.G., (2018). Vertical Farming Using Hydroponic System: Toward a Sustainable Onion Production in Nueva Ecija, Philippines. Open J. Ecol. 08, 25–41. https://doi.org/10.4236/oje.2018.81003

Paulitz, T.C., Bélanger, R.R., (2001). B IOLOGICAL C ONTROL IN G REENHOUSE S YSTEMS. Annu. Rev. Phytopathol. 39, 103–133. https://doi.org/10.1146/annurev.phyto.39.1.103

Peterson, M.J., Sutherland, J.R., Tuller, S.E., (1988). Greenhouse environment and epidemiology of grey mould of containergrown Douglas-fir seedlings. Can. J. For. Res. 18, 974–980.

Roberts, M.R., Paul, N.D., (2006). Seduced by the dark side: integrating molecular and ecological perspectives on the influence of light on plant defence against pests and pathogens. New Phytol. 170, 677–699. https://doi.org/10.1111/j.1469-8137.2006.01707.x

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W., (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci. 111, 3268–3273. https://doi.org/10.1073/pnas.1222463110

Santini, A., Bartolini, E., Schneider, M., de Lemos, V.G., (2021). The crop growth planning problem in vertical farming. Eur. J. Oper. Res. 294, 377–390.

Smit, J., Nasr, J., Ratta, A., (1996). Urban agriculture: food, jobs and sustainable cities. N. Y. USA 2, 35–37.

Stacey, D.L., (1977). 'Banker' Plant Production of *Encarsia formosa* Gahan and its Use in the Control of Glasshouse Whitefly on Tomatoes. Plant Pathol. 26, 63–66.

Suzuki, N., Rivero, R.M., Shulaev, V., Blumwald, E., Mittler, R., (2014). Abiotic and biotic stress combinations. New Phytol. 203, 32–43. https://doi.org/10.1111/nph.12797

Symondson, W.O.C., Sunderland, K.D., Greenstone, M.H., (2002). Can Generalist Predators be Effective Biocontrol Agents? Annu. Rev. Entomol. 47, 561–594.

Takeshima, H., Joshi, P.K., (2019). Protected agriculture, precision agriculture, and vertical farming: Brief reviews of issues in the literature focusing on the developing region in Asia. Intl Food Policy Res Inst.

Torr, S.J., Hall, D.R., Phelps, R.J., Vale, G.A., (1997). Methods for dispensing odour attractants for tsetse flies (Diptera: Glossinidae). Bull. Entomol. Res. 87, 299–311.

Touliatos, D., Dodd, I.C., McAinsh, M., (2016). Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. Food Energy Secur. 5, 184–191.

Van Delden, S.H., SharathKumar, M., Butturini, M., Graamans, L.J.A., Heuvelink, E., Kacira, M., Kaiser, E., Klamer, R.S., Klerkx, L., Kootstra, G., (2021). Current status and future challenges in implementing and upscaling vertical farming systems. Nat. Food 2, 944–956.

Vanachter, A., Van Wambeke, E., Van Assche, C., (1982). Potential danger for infection and spread of root diseases of tomatoes in hydroponics. Nutr. Film Tech. Substrates XXI IHC 133 119–128.

Wheeler, T., Von Braun, J., (2013). Climate Change Impacts on Global Food Security. Science 341, 508–513. https://doi.org/10.1126/science.1239402

Whitfield, A.E., Falk, B.W., Rotenberg, D., (2015). Insect vector-mediated transmission of plant viruses. Virology 479, 278–289.

Wicharuck, S., Khongdee, N., Pripanakul, T., Whangchai, N., Pimpimol, T., Chaichana, C., (2023). Vertical farming: A potential farming practice for lettuce production. Chil. J. Agric. Res. 83, 248–259.

Yang, Z., Chu, L., Wang, C., Pan, Y., Su, W., Qin, Y., Cai, C., (2023). What drives the spatial heterogeneity of cropping patterns in the Northeast China: The natural environment, the agricultural economy, or policy? Sci. Total Environ. 905, 167810. https://doi.org/10.1016/j.scitotenv.2023.167810

Zinnen, T.M., (1988). Assessment of plant diseases in hydroponic culture. Plant Dis. 72, 96–99.