Urban Agriculture in Review: Hydroponics, Aeroponics, Aquaponics

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Introduction

Hydroponic, aeroponic, and aquaponic urban agricultural systems are often discussed as promising alternatives to conventional field production (Barbosa et al., 2015; Specht et al., 2014; Teoh et al., 2024). However, these systems are not interchangeable. Each uses different mechanisms to deliver water and nutrients to plants, and each involves distinct trade-offs in environmental control, stability, yield, and scalability (Dunn, 2025; Garzón et al., 2023; Maucieri et al., 2018; Okomoda et al., 2023). Because of these differences, their value cannot be judged by efficiency alone. Instead, each system must be evaluated based on the production context, including the goals, limitations, and resources of the application (Wilhelm, J. A., & Smith, R. G., 2018; Specht et al., 2014; Teoh et al., 2024). This paper compares hydroponic, aeroponic, and aquaponic systems to examine how their strengths and limitations make them better suited for different agricultural settings.

Background

We live in an ever-changing world where the population is rapidly increasing, technology is advancing, and cities are growing bigger than ever. The United Nations predicts that by 2050, 66% of the world's population will be living in cities (United Nations, 2014). With this comes pre-existing problems that will only be exacerbated, namely: food, water, and land scarcity. Agriculture accounts for approximately 69% of global freshwater use, making water one of the central constraints on future food production (Food and Agriculture Organization, n.d.). As humans increasingly migrate to cities, these resource pressures have intensified interest in urban agriculture as a strategy to produce food more efficiently and closer to areas of consumption.

Defined as "the cultivation, processing, and distribution of agricultural products (food or non-food) in urban and suburban areas" (United States Department of Agriculture, n.d.), urban agriculture can take shape in many ways and exist in diverse environments across the globe, from the deserts of Israel to cultural hotspots like Atlanta, Georgia, USA (Montgomery, 2025). There's even evidence that 'urban agriculture' existed as early as 3,500 B.C. in Mesopotamia, and although urban agriculture there consisted of aqueducts and basic technology, they were able to provide food locally, and it was nonetheless urban (Aurora University, 2019). However, when most people think of urban agriculture, they may picture futuristic, high-tech robots gardening in a city with flying cars. Even though this seems like an imaginary

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My name is Skylar Griffith, and I am an undergraduate student studying Biological Sciences. I grew up in San Marcos, California, where I transferred from a community college, and I currently work as an intern at the USDA Biological Control of Insects research lab. On campus, I participate in a Jazz Combo playing drums, intramural sports, and the TEAM transfer club. I'm interested in all aspects of science and plan to go on to graduate school after my last year here.

reality, current research is moving urban agriculture closer to this idea through automated systems that use sensors, monitoring technology, and other advanced machinery (Garzón et al., 2023; Palande et al., 2018). The most discussed urban agricultural systems include hydroponics, aeroponics, and aquaponic systems (Barbosa et al., 2015; Specht et al., 2014; Teoh et al., 2024).

The benefits of these systems are numerous and may provide solutions to our future food problems. Across the board, these systems are more water and energy-efficient, produce higher yields, require less land, and can be more profitable than traditional farming models (Barbosa et al., 2015; Goh et al., 2023; Love et al., 2015; Specht et al., 2014). Urban agriculture in general can also provide more opportunities for community involvement and fresh, local produce for urbanites (Draper, 2010). This matters not just because fresh produce tastes better, but studies estimate that fresh produce travels 1,500 food miles before being eaten (Harris, 2022). Furthermore, 10% of all fossil fuels are used for food transportation (Hill, 2008). If produce can be grown in the city that buys it, these numbers could be reduced, and large cities could contribute to a more sustainable system. Unfortunately, due to the high-tech requirements for urban systems, they can often have a high initial setup and operating cost, require more skilled operators, and have more complicated maintenance procedures (Lee, S., & Lee, J., 2019). This makes executing these systems difficult; however, with adequate funding, proper implementation, continuing advancements, and time, the advantages can far outweigh the disadvantages, and urban systems can become the future of agriculture (Gunapala et al., 2025).

Variables

The systems examined in this paper are evaluated through four major variables: control, stability, yield, and scalability. Control refers to the degree to which growers can regulate plant growth conditions, including nutrient delivery, pH, light, temperature, humidity, and other factors that influence photosynthesis and consumable biomass production (Lewis Ivey et al., 2025; Wortman, 2015). Controlled environment agriculture is built around this principle, using enclosed or partially enclosed systems to manipulate inputs such as light, nutrients, carbon dioxide, temperature, and humidity in order to optimize plant performance (Lewis Ivey et al., 2025). However, increasing the number of controllable variables also increases dependence on monitoring, infrastructure, and precise system management. Stability refers to the ability of a system to maintain function when conditions change or components fail. This is closely tied to buffering capacity, or the ability of a growing environment to resist sudden changes in root-zone conditions (Ferentinos & Albright, 2003; Oklahoma State University Extension, n.d.). Systems that depend on continuous delivery of water, oxygen, and nutrients are more sensitive to disruptions such as pump failure, power loss, or interrupted flow. Reviews of highly engineered cultivation systems note that this dependence on continuous technical operation is one of the key trade-offs associated with high-efficiency production (Tafesse et al., 2021; Garzón et al., 2023).

Yield refers to the amount of usable crop output a system produces, making it one of the clearest measures of overall system performance (Barbosa et al., 2015; Goh et al., 2023). Yield is often measured through final harvest weight or marketable biomass which is shaped by the system's ability to produce year-round, speed of growth, and the maintenance of favorable growing conditions throughout production (Wortman, 2015). Disruptions in water availability, nutrient delivery, pH, or electrical conductivity can rapidly affect plant physiology (Fathidarehnijeh et al., 2023; Wortman, 2015). Reduced water availability lowers cell turgor, impairs nutrient transport, and suppresses photosynthesis (Chaves et al., 2002; Fathidarehnijeh et al., 2023; Qiao et al., 2024). In one experimental study, low electrical conductivity combined with high pH reduced chlorophyll content and marketable yield, with yield reductions reaching 44% in basil and 76% in kale, thus demonstrating how suboptimal nutrient or solution conditions can quickly translate into major production losses (Wortman, 2015). Yield is useful in this comparison because it shows not only how productive a system can be under ideal conditions, but also how strongly production can decline when the system fails to maintain proper growing conditions.

Scalability refers to the ability to expand a system toward commercial production while maintaining performance at a

tmanageable cost. Systems that provide high levels of environmental control often require more infrastructure, monitoring, and maintenance, which can complicate scaling even when biological efficiency is high (Lewis Ivey et al., 2025; Garzón et al., 2023). Thus, scalability depends not only on productive capacity but also on the trade-offs among precision, operational burden, and economic feasibility (Engle, 2015; Garzón et al., 2023; Love et al., 2015).
Taken together, these variables show that efficiency and resilience are often in tension. Systems designed for greater control and faster resource delivery may support strong plant performance under ideal conditions, but they may also become more vulnerable when key components are disrupted. Conversely, systems with greater natural buffering may offer less precision but greater resilience. The central trade-off, therefore, is between optimization and vulnerability; the same features that increase efficiency can also increase dependence on uninterrupted and carefully managed system function. With this framework established, the following sections examine hydroponic, aeroponic, and aquaponic urban agricultural systems individually to evaluate how each system navigates these trade-offs.

Hydroponics

Hydroponics involves suspending a plant above nutrient-rich water, either with or without a soil-less substrate like expanded clay, coconut coir, perlite, vermiculite, or wood (Dunn, 2025). The base of the plant is contained in the substrate, which provides mechanical support, aeration, water retention, and nutrient ion distribution, while the roots hang in the water-nutrient solution (Sesanati et al., 2026). There are many different methods for hydroponic systems that are highly customizable to optimize plant health and yield depending on the species (Varghese, 2024). The nutrient solution can either be in an open system, where new water is consumed, or a closed system, where water is recirculated (Fathidarehnijeh et al., 2023). The combination of substrate selection, nutrient solution, vertical versus horizontal setup, and the environment can all have an effect on yield, which studies show can produce up to 11 times higher yield than traditional soil-based farming, depending on the plant and configuration (Barbosa et al., 2015; Goh et al., 2023; Gurung et al., 2019; Sardare, 2013).

Since hydroponics is considered a high-tech agricultural system, there is a lot of control and precision involved. Major external factors, like climate and soil, are removed, and the entire system can be manually controlled. Water from the system can be removed, replaced, or cleaned; nutrients and disease control agents can be directly distributed to the plant through the water solution; and conditions like temperature, pH, and moisture can be adjusted to best suit the plant's needs (Paulitz, 1997). Another high-tech aspect that increases control is the use of sensors that allow for automation. With the use of electrical conductivity probes, pH sensors, water temperature sensors, air temperature/humidity sensors, and Internet of Things (IoT) network, the system can be fully monitored (Palande et al., 2018). Each of these sensors monitors a crucial factor to plant health, and with the hands-off ability to control the values of these properties, it can show improved plant growth and reduce labor costs.

Depending on the type of configuration used, varying amounts of mechanical and biological failure are inevitable. Some areas of mechanical failure can be water pumps, nutrient pumps, sensors, lighting, and filtration. Fortunately, the use of the aforementioned sensors that can detect and diagnose mechanical faults in real time represent ways to monitor for these types of failures, making maintenance easier (Ferentinos & Albright, 2003). Systems can also fail biologically through lack of nutrients, root hypoxia, root rot, pH imbalance, and limitation in light (especially in vertical farming) (Balliu et al., 2021). Due to the lack of soil in hydroponic systems, soil-born bacteria and diseases are eliminated, which reduces the need for pesticides. However, diseases like root rot are caused by other bacterial and fungal infections, and in closed systems, where water is recirculating, plants are susceptible (Paulitz, 1997). There are ways to prevent the spread of disease by using a combination of methods, including UV radiation, filtration, ozonation, sanitation, and biocontrol agents (Paulitz, 1997).

Lastly, the cost of hydroponic farming is an important consideration when discussing viable implementation and scalability. There are multiple factors to consider when calculating costs, such as initial setup costs, operational costs, land costs, maintenance costs, energy consumption, water consumption, and profits associated with yield (Janakiballav

Mishra et al., 2024). As mentioned earlier, hydroponics produces a higher yield than traditional farming, which directly relates to higher profits. Looking at water consumption, when considering the higher yields of hydroponics, it uses about 13 times less water than traditional farming (Barbosa et al., 2015). On the contrary, hydroponics requires about 80 times as much electricity, with 82% of it being used for heating and cooling, 17% for lighting, and <1% for water pumps (Barbosa et al., 2015). Since hydroponics doesn't require large plots of arable land, land costs are greatly reduced, and the opportunity for the location of hydroponic farm operations is much greater than that of traditional farms. The highest cost of hydroponics is the initial setup costs, which a study calculated to be more expensive than traditional farming due to investments in higher technology, but found the operational costs to be cheaper (Janakiballav Mishra et al., 2024). It appears that although hydroponics has these higher initial costs, over time, it would be more profitable and provide numerous other benefits that would be worth waiting for the return on investment.

Aeroponics

Aeroponics is a system of soilless agriculture that involves the suspension of plants within the air, with the roots exposed and periodically misted with nutrients. This misting system gives aeroponics complete environmental control of the water and nutrient uptake of the plants (Lakhiar et al, 2020). The lack of soil means that aeroponics is a highly efficient system that is sustainable in terms of its price, production, time, and land area usage. Soilless production is more cost-effective, results in higher yields, produces quicker harvests from smaller areas of land, and saves more water compared to other soilless systems (Lakhiar et al, 2020).

Aeroponics is also sustainable in its low environmental impacts due to its lack of need for soil maintenance and fertilizers, which can cause runoff to pollute the environment. Despite needing less maintenance, aeroponic systems do come with a high level of complexity. Due to the lack of a physical buffering medium (soil), highly accurate regulation of nutrient concentration, ionic composition, and dissolved oxygen levels is crucial for plant health and growth and requires real-time monitoring (Chu & Wan, 2026). Similarly, aeroponics has high water and energy demands and needs reliable access to these resources, which results in a high capital investment (Chu & Wan, 2026). One of the downsides of these complexities is that it requires technical expertise, which is why aeroponics is best suited for dense urban cities or research-focused areas like universities, which will have people trained to use aeroponics. Small cities or rural settings would not be as realistic due to the likely lack of trained expertise and fewer resources available to maintain complex systems.

In terms of efficiency, aeroponics provides real-time data that enables precise control, early issue detection, resource efficiency, and informed decision making; ultimately leading to improved crop yields, reduced resource consumption, and more sustainable agricultural practices (Garzón et al, 2023). Aeroponics also make efficient usage of space within greenhouses or controlled environmental spaces in urban agriculture settings and effectively exploits the vertical space and air humidity balance to optimize the development of roots, tubers, and foliage (Gopinath et al, 2017). Efficient usage of space in urban settings makes the most of limited water supplies to maximize crop yields. Due to this high efficiency, aeroponics can also be utilized to grow high-value crops such as potatoes, yams, lettuce, and other leafy vegetables, which normally cannot be grown effectively in an urban context (Kim et al., 2024). This is due to the advanced misting technologies providing 100% oxygen delivery to the roots and stem to promote efficient growth (Gopinath et al, 2017). Maximum oxygen delivery is a major reason why aeroponics excels in terms of crop yield and can produce three times the growth of traditional farming.

In terms of cost and scalability, the benefit-cost ratio is 1.14, which translates to profitability and economic viability at both small and large scales (Singha et al., 2026). Like most soilless systems, aeroponics has a high initial cost due to the complex technology required, but has high profitability when utilized to grow high-value crops. A study also found that the application of these technologies were applied with advanced integration 57% of the time, which means new technologies were used to create new processes that enhanced the system's efficiency, rentability, and sustainability concentrations (Korbee et al., 2025). These findings suggest that aquaponic yield is not uniformly lower than hydroponic yield, but it is more dependent on crop choice and system management.

Scalability is one of the major challenges for aquaponics. Although the system can improve resource efficiency through nutrient recycling, scaling it requires more infrastructure, labor, and technical management than simpler production systems. Commercial aquaponic systems may require large fish tanks, plant raceways, filtration systems, pumps, and monitoring equipment (Engle, 2015; Tokunaga et al., 2015). These infrastructure needs can be considerable in system establishment costs. Across U.S. aquaponics studies, total investment costs ranged from $58,760 to $1,020,536, annual net returns ranged from losses of more than $11,000 to profits of $278,038, and rates of return ranged from 0% to 27% (Engle, 2015). Labor is also a major constraint, accounting for 46% of operating costs and 40% of total annual costs in one commercial aquaponics analysis (Tokunaga et al., 2015; Engle, 2015). Therefore, while aquaponics has strong potential for sustainable nutrient recycling and specialized crop production, its broader scalability depends on whether producers can manage its biological complexity, infrastructure costs, labor demands, and variable profitability.

Implications

The comparison of hydroponic, aeroponic, and aquaponic systems shows that urban agriculture should be evaluated as a practical planning decision rather than only as a technological advancement. These systems have strong potential to support local food production, reduce food miles, and improve access to fresh produce, especially as urbanization, industrialization, and land-use pressures continue to limit conventional agricultural space (Audate et al., 2019; Harris, 2022; Hill, 2008; Joshi et al., 2022; United Nations Department of Economic and Social Affairs, Population Division, 2019). However, their success depends on whether the system fits the setting's available land/space, funding, labor, technical support, water access, and energy reliability (Wilhelm, J. A., & Smith, R. G., 2018; Specht et al., 2014; Teoh et al., 2024).

In large cities, urban agriculture may help address limited land availability and high demand for fresh produce (Wilhelm, J. A., & Smith, R. G., 2018; Specht et al., 2014; Teoh et al., 2024). Controlled systems can be especially useful because they allow crops to be grown year-round rather than being limited by seasonal field conditions (Lewis Ivey et al., 2025; Specht et al., 2014). However, this benefit comes with practical demands. Systems that rely on pumps, climate control, misting, artificial lighting, or continuous monitoring require reliable infrastructure and skilled maintenance (Garzón et al., 2023; Lewis Ivey et al., 2025; Palande et al., 2018). Therefore, the main implication for large cities is that high-efficiency systems can be valuable, but only when their energy, labor, cost, and technology requirements can be supported over time.

Educational settings like K-12 schools, colleges, and universities create a unique opportunity by allowing urban agriculture to serve more than one purpose. In addition to producing food, these systems can support research, education, sustainability programs, and student engagement (Audate et al., 2019; Draper & Freedman, 2010). In K-12 school settings, gardens and controlled growing systems can also be used as hands-on learning tools that connect students to food systems, environmental science, nutrition, and community health (Audate et al., 2019; Draper & Freedman, 2010). College and university students may benefit from more complex systems as they allow the study of nutrient cycling, water conservation, plant growth, system design, and environmental trade-offs (Graber & Junge, 2009; Lewis Ivey et al., 2025; Maucieri et al., 2018). This makes educational campuses important testing grounds for controlled environment agriculture, especially when faculty expertise, student labor and learning, and institutional sustainability goals help support long-term maintenance.

Small cities and rural areas face different constraints. These areas may have more available land, but they may not have the same funding, technical labor, or infrastructure needed for advanced controlled systems (Engle, 2015; Garzón et al., 2023; Teoh et al., 2024). In these settings, lower cost and lower maintenance approaches may be more realistic than systems that require constant technical oversight (Engle, 2015; Wilhelm, J. A., & Smith, R. G., 2018; Teoh et al., 2024). In these settings, lower cost and lower maintenance approaches may be more realistic than systems that require constant technical oversight (Engle, 2015; Wilhelm, J. A., & Smith, R. G., 2018; Teoh et al., 2024). Urban agriculture may be most valuable when it supports community access, local participation, and small-scale production rather than maximum yield per square foot (Audate et al., 2019; Draper & Freedman, 2010; Wilhelm, J. A., & Smith, R. G., 2018). Controlled systems may still be useful, but their benefits struggle to outweigh their start-up costs and maintenance demands in rural areas.

These implications show that urban agriculture cannot be treated as a complete replacement for traditional farming. Many staple crops, fruit trees, and livestock require land and conditions that are not realistic for most urban production systems (Wilhelm, J. A., & Smith, R. G., 2018; Specht et al., 2014; Teoh et al., 2024). Instead, urban agriculture is best understood as a complementary strategy that can strengthen local food systems when matched to the needs and resources of the community (Audate et al., 2019; Wilhelm, J. A., & Smith, R. G., 2018; Specht et al., 2014). Its future value depends less on whether a system is technologically advanced and more on whether it can remain practical, affordable, and sustainable in the setting where it is used.

Conclusion

Hydroponic, aeroponic, and aquaponic systems each offer different strengths and limitations within urban agriculture (see Table 1.). Hydroponics provides strong environmental control, reliable production, and clearer pathways for commercial scaling, making it especially useful for large cities where consistent, high-volume production is needed in limited space. Aeroponics offers high efficiency through rapid growth, strong oxygen access, and reduced water use, which may make it valuable in dense urban areas or research-focused settings where space and water conservation are major priorities. However, aeroponics' reliance on misting technology also makes it more vulnerable to technical failure, so it may be less practical in settings without strong technical support. Aquaponics is best suited for contexts

Table 1. *Comparison of Hydroponic, Aeroponic, and Aquaponic systems to the variables discussed; Control, Stability, Yield, and Scalability, along with relevant subcategories.*

Variables	Sub-Categories	Hydroponics	Aeroponics	Aquaponics
Control	**Environmental**	Complete	Complete	Limited
Stability	**Biological failures**	Medium	Low	High
	Complexity	Complex	Complex	Most Complex
Yield	**Land usage**	Low	Low	Medium
	Yield	High	Higher	Medium
Scalability	**Initial cost**	High	High	Very High
	Profitability	High	High	Medium
	Scale of production	High	Medium	Small

Note: Each category is compared using relative, general measures that best characterize the differences among each system. Environmental control refers to the level of control of the environment within the system which includes control of different factors such as pH, nutrient level, moisture levels, climate control, and artificial lighting. Biological failures address susceptibility to diseases, pests, and system imbalances. Complexity corresponds to how many biological and mechanical components are involved in the system. Land usage describes how much land is required for the system, which relates to its ability to be vertically positioned. Yield compares the quantity, size, and speed of food produced, which is high in all the systems compared to traditional farming, with small differences among them. High initial cost only looks at the cost of starting these systems and does not include operational costs. Profitably relates to yield by comparing it to the cost, maintenance, and overall profit margins. Scale of production measures how large each system can get and still be feasible, profitable, and manageable.

where sustainability, education, and resource cycling are major goals, such as college/university campuses, demonstration facilities, or community-based food projects. By integrating plant production with fish farming, aquaponics can model nutrient recycling and closed-loop production, although its biological complexity makes it more management-intensive than simpler systems.

Overall, no single system is best in every context. Large cities may benefit most from hydroponics or aeroponics when strong technical support is available, since these systems can support high production in limited space. College campuses may be especially well suited for aquaponics and aeroponics because they can support education, research, sustainability, and community engagement. Therefore, the most effective approach is not to identify one superior system, but to match each system's balance of control, stability, yield, and scalability to the needs and limitations of the setting. As more research is conducted, technology evolves and equipment becomes more accessible, which may lead to one system becoming significantly better than the other. Until then, each system discussed has a unique place in today's agricultural urban landscape.

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References

Aslanidou, M., Elvanidi, A., Mourantian, A., Levizou, E., Mente, E., & Katsoulas, N. (2024). Evaluation of productivity and efficiency of a large-scale coupled or decoupled aquaponic system. Scientia Horticulturae, 337, 113552. https://doi.org/10.1016/j.scienta.2024.113552

Audate, P. P., Fernandez, M. A., Cloutier, G., & Lebel, A. (2019). Scoping review of the impacts of urban agriculture on the determinants of health. BMC Public Health, 19(1). https://doi.org/10.1186/s12889-019-6885-z

Aurora University. (2019, October 14). The History of Urban Agriculture and Urban Farming Policies. Aurora University. https://online.aurora.edu/history-of-urban-agriculture/

Balliu, A., Zheng, Y., Sallaku, G., Fernández, J. A., Gruda, N. S., & Tuzel, Y. (2021). Environmental and Cultivation Factors Affect the Morphology, Architecture and Performance of Root Systems in Soilless Grown Plants. Horticulturae, 7(8), 243. https://doi.org/10.3390/horticulturae7080243

Barbosa, G., Gadelha, F., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., … Halden, R. (2015). Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. International Journal of Environmental Research and Public Health, 12(6), 6879–6891. https://doi.org/10.3390/ijerph120606879

Chaves, M. M., Pereira, J. S., Maroco, J., Rodrigues, M. L., Ricardo, C. P. P., Osório, M. L., Carvalho, I., Faria, T., & Pinheiro, C. (2002). How plants cope with water stress in the field: Photosynthesis and growth. Annals of Botany, 89(7), 907–916. https://doi.org/10.1093/aob/mcf105

References (continued)
Chu, S.W., & Wan, T.J. (2026). Advancing Sustainable Agriculture Through Aeroponics: A Critical Review of Integrated Water–Energy–Nutrient Management and Environmental Impact Mitigation. Agriculture, 16(2), 265. https://doi.org/10.3390/agriculture16020265

Draper, C., & Freedman, D. (2010). Review and Analysis of the Benefits, Purposes, and Motivations Associated with Community Gardening in the United States. Journal of Community Practice, 18(4), 458–492. https://doi.org/10.1080/10705422.2010.519682

Dunn, B. (2025, July). Hydroponics - Oklahoma State University | Oklahoma State University. Retrieved from Ferguson College of Agriculture website: https://extension.okstate.edu/fact-sheets/hydroponics

Engle, C. R. (2015, July). Economics of aquaponics (SRAC Publication No. 5006). Southern Regional Aquaculture Center.
https://aquaculture.mgcafe.uky.edu/sites/aquaculture.ca.uky.edu/files/srac_5006_economics_of_aquaponics_0.pdf

Fathidarehnijeh, E., Nadeem, M., Cheema, M., Thomas, R., Krishnapillai, M., & Galagedara, L. (2023). Current perspective on nutrient solution management strategies to improve the nutrient and water use efficiency in hydroponic systems. Canadian Journal of Plant Science, 104. https://doi.org/10.1139/CJPS20230034

Ferentinos, K. P., & Albright, L. D. (2003). Fault Detection and Diagnosis in Deep-trough Hydroponics using Intelligent Computational Tools. Biosystems Engineering, 84(1), 13–30. https://doi.org/10.1016/s1537-5110(02)00232-5

Food and Agriculture Organization of the United Nations. (n.d.). Institutional framework. AQUASTAT. https://www.fao.org/aquastat/en/overview/methodology/institutionalframework/

Garzón, J., Montes, L., Garzón, J., & Lampropoulos, G. (2023). Systematic Review of Technology in Aeroponics: Introducing the Technology Adoption and Integration in Sustainable Agriculture Model. Agronomy, 13(10), 2517. https://doi.org/10.3390/agronomy13102517

Goh, Y. S., Hum, Y. C., Lee, Y. L., Lai, K. W., Yap, W.-S., & Tee, Y. K. (2023). A metaanalysis: Food production and vegetable crop yields of hydroponics. Scientia Horticulturae, 321(321), 112339. https://doi.org/10.1016/j.scienta.2023.112339

Gopinath, P., Vethamoni, P. I., & Gomathi, M. (2017). Aeroponics soilless cultivation system for vegetable crops. Chemical Science Review and Letters, 6(22), 838-849. https://www.semanticscholar.org/paper/Aeroponics-Soilless-Cultivation-System-for-Crops-Gopinath-Vethamoni/ccac729fae5437d40ef9615be771fc3948c375e2

Graber, A., & Junge, R. (2009). Aquaponic systems: Nutrient recycling from fish wastewater by vegetable production. Desalination, 246(1–3), 147–156. https://doi.org/10.1016/j.desal.2008.03.048

Gunapala, R., Gangahagedara, R., Wanasinghe, W. C. S., Samaraweera, Anjalika U, Gamage, A., Rathnayaka, C., … Merah, O. (2025). Urban agriculture: A strategic pathway to building resilience and ensuring sustainable food security in cities. Farming System, 3(3), 100150. https://doi.org/10.1016/j.farsys.2025.100150

Gurung, C., Bhandari, J., & Gurung, A. (2019). Evaluation of Hydroponic Cultivation Techniques as a Supplement to Conventional Methods of Farming. 6, 57–64. 32.2022.0703022.

References (continued)

Harris, L. (2022, April 27). What Are Food Miles? | Connect4Climate. Connect 4 Climate. https://www.connect4climate.org/initiative/what-are-food-miles

Hill, H. (2008). Food Miles: Background and Marketing. ATTRA. https://attra.ncat.org/publication/food-miles-background-and-marketing/

Janakiballav Mishra, S., Rout, D., & Sahoo, D. (2024). Analysing the Economic Viability of Hydroponic Farming: A Comparative Cost-Benefit Analysis. International Journal of Progressive Research in Engineering Management and Science, 4(6), 1806–1811. https://doi.org/10.58257/ijprems35128

Joshi, Dipesh & Nainabasti, Anjal & Bhandari, Rita & Awasthi, Prakash & Banjade, Dinanath & Malla, Santoshi & Subedi, Bishesh. (2022). A review on soilless cultivation: The hope of urban agriculture. Archives of Agriculture and Environmental Science. 7. 473-481. 10.26832/245666

Kim, J., Park, H., Seo, C., Kim, H., Choi, G., Kim, M., Kim, B., & Lee, W. (2024). Sustainable and Inflatable Aeroponics Smart Farm System for Water Efficiency and High-Value Crop Production. Applied Sciences, 14(11), 4931. https://doi.org/10.3390/app14114931

Korbee, N., Bautista, B., García-Sánchez, M., Cobos, P., Ferres-García, J. L., Figueroa, F. L., & Medrano, E. (2025). Evaluating hydroponics and aquaponics: Comparative insights into sustainability and strawberry quality. Agricultural Water Management, 312, 109412. https://doi.org/10.1016/j.agwat.2025.109412

Lakhiar, Imran & Gao, Jianmin & Syed, Tabinda & Chandio, Farman Ali & Tunio, Mazhar & Ahmad, Fiaz & Solangi, Kashif. (2020). Overview of the aeroponic agriculture – An emerging technology for global food security. International Journal of Agricultural and Biological Engineering. 13. 1-10. 10.25165/j.ijabe.20201301.5156.

Lee, S., & Lee, J. (2015). Beneficial bacteria and fungi in hydroponic systems: Types and characteristics of hydroponic food production methods. Scientia Horticulturae, 195, 206–215. https://doi.org/10.1016/j.scienta.2015.09.011

Lewis Ivey, M. L., Rivas, G., Kubota, C., Samarakoon, U., Kleinhenz, M., Quintero Fonseca, H., & Ilic, S. (2025, May 23). What is controlled environment agriculture (CEA)? Ohioline. https://ohioline.osu.edu/factsheet/hyg-5819

Love, D. C., Fry, J. P., Li, X., Hill, E. S., Genello, L., Semmens, K., & Thompson, R. E. (2015). Commercial aquaponics production and profitability: Findings from an international survey. Aquaculture, 435, 67–74. https://doi.org/10.1016/j.aquaculture.2014.09.023

Maucieri, C., Nicoletto, C., Junge, R., Schmautz, Z., Sambo, P., & Borin, M. (2018). Hydroponic systems and water management in aquaponics: A review. Italian Journal of Agronomy, 13(1), 1012. https://doi.org/10.4081/ija.2017.1012

Montgomery, M. (2025, September 10). Urban Farming Takes Root in Atlanta (T. Harte, Ed.). Retrieved from Atlanta History Center website: https://www.atlantahistorycenter.com/blog/urban-farming-takes-root-in-atlanta/

Mourantian, A., Aslanidou, M., Mente, E., Katsoulas, N., & Levizou, E. (2025). Capturing the physiological and growth dynamics of cucumber cultivated in coupled and decoupled aquaponic systems. Scientia Horticulturae, 351, 114377. https://doi.org/10.1016/j.scienta.2025.114377

References (continued)

Oklahoma State University Extension. (n.d.). Soil pH and buffer index. Oklahoma State University. https://extension.okstate.edu/fact-sheets/soil-ph-and-buffer-index.html

Okomoda, V. T., Oladimeji, S. A., Solomon, S. G., Olufeagba, S. O., Ogah, S. I. O., & Ikhwanuddin, M. (2023). Aquaponics production system: A review of historical perspective, opportunities, and challenges of its adoption. Food Science & Nutrition, 11(3), 1157–1165. https://doi.org/10.1002/fsn3.3154

Palande, V., Zaheer, A., & George, K. (2018). Fully Automated Hydroponic System for Indoor Plant Growth. 2017 INTERNATIONAL CONFERENCE on IDENTIFICATION, INFORMATION and KNOWLEDGE IN the INTERNET of THINGS, 129, 482–488. https://doi.org/10.1016/j.procs.2018.03.028

Patloková, K., & Pokluda, R. (2024). Optimization of plant nutrition in aquaponics: The impact of Trichoderma harzianum and Bacillus mojavensis on lettuce and basil yield and mineral status. Plants, 13(2), 291. https://doi.org/10.3390/plants13020291

Paulitz, T. C. (1997). Biological Control of Root Pathogens in Soilless and Hydroponic Systems. HortScience, 32(2), 193–196. https://doi.org/10.21273/HORTSCI.32.2.193

Qiao, M., Hong, C., Jiao, Y., Hou, S., & Gao, H. (2024). Impacts of drought on photosynthesis in major food crops and the related mechanisms of plant responses to drought. Plants, 13(13), 1808. https://doi.org/10.3390/plants13131808

Rašković, B., Gebauer, R., Folorunso, E. A., Božić, G., Velíšek, J., Dvořák, P., Bořík, A., Grabic, R., & Mráz, J. (2022). Botanical and microbial insecticides application in aquaponics: Is there a risk for biofilter bacteria and fish? Frontiers in Marine Science, 9, 1055560. https://doi.org/10.3389/fmars.2022.1055560

Sardare, M. (2013). A Review on Plant without Soilhydroponics. International Journal of Research in Engineering and Technology, 02, 299–304. https://doi.org/10.15623/ijret.2013.0203013

Schmautz, Z., Graber, A., Jaenicke, S., Goesmann, A., Junge, R., & Smits, T. H. M. (2017). Microbial diversity in different compartments of an aquaponics system. Archives of Microbiology, 199, 613–620. https://doi.org/10.1007/s00203-016-1334-1

Sesanti, R. N., Purwanto, E., Samanhudi, & Sudadi. (2026). Sustainable hydroponic systems: Effects of nutrient and substrate variations on plant growth and rhizosphere bacterial morphological diversity. Journal of Ecological Engineering, 27(3), 116–131. https://doi.org/10.12911/22998993/211939

Singha, A., Tasnim, Z., Maliha, M.A. et al. (2026). Exploring the feasibility of vertical aeroponic tower constructed from locally available materials for sustainable farming in Bangladesh.Bull Natl Res Cent 50, 26 (2026). https://doi.org/10.1186/s42269-026-01416-9

Specht, K., Siebert, R., Hartmann, I. et al. (2014). Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. Agric Hum Values 31, 33–51 (2014). https://doi.org/10.1007/s10460-013-9448-4

Tafesse, E. G., & Ayele, M. K. (2021). Aeroponic systems: A unique tool for estimating plant water relations and NO3 uptake in response to salinity stress. Plant Methods, 17, 29. https://doi.org/10.1186/s13007-021-00734-8

References (continued)

Teoh, S. H., Wong, G. R., & Mazumdar, P. (2024). A review on urban farming: Potential, challenges and opportunities. Innovations in Agriculture, 7, 1–11. https://doi.org/10.3897/ia.2024.127816

Tokunaga, K., Tamaru, C., Ako, H., & Leung, P. S. (2015). Economics of small-scale commercial aquaponics in Hawai‘i. Journal of the World Aquaculture Society, 46(1), 20–32. https://doi.org/10.1111/jwas.12173 47

United Nations (2014). World urbanization prospects: The 2014 revision, highlights. Department of Economic and Social Affairs. Population Division, United Nations, 32, 1-1. https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/files/documents/2020/Oct/unpd_2014_wup-report.pdf

United Nations, Department of Economic and Social Affairs, Population Division. (2019). World urbanization prospects 2018: Highlights (ST/ESA/SER.A/421). United Nations. https://population.un.org/wup/assets/WUP2018-Highlights.pdf

United States Department of Agriculture. (n.d.). Urban Agriculture | National Agricultural Library. Www.nal.usda.gov. https://www.nal.usda.gov/farms-and-agriculturalproduction-systems/urban-agriculture

Varghese, A. B., & P, D. M. (2024). Enhancing Hydroponic Production: A Review of Plant Growth and Health Monitoring System. 2024 Second International Conference on Intelligent Cyber Physical Systems and Internet of Things (ICoICI), 492–498. https://doi.org/10.1109/ICoICI62503.2024.10696642

Wilhelm, J. A., & Smith, R. G. (2018). Ecosystem services and land sparing potential of urban and peri-urban agriculture: A review. Renewable Agriculture and Food Systems, 33(5), 481–494. https://www-jstor-org.proxy.mul.missouri.edu/stable/26502650

Wortman, S. E. (2015). Crop physiological response to nutrient solution electrical conductivity and pH in an ebb-and-flow hydroponic system. Scientia Horticulturae, 194, 34–42. https://doi.org/10.1016/j.scienta.2015.07.045