Artifacts

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TABLE OF CONTENTS

Beyond Technology: How Governance and Culture Shape Wastewater Reuse in the United States and Israel

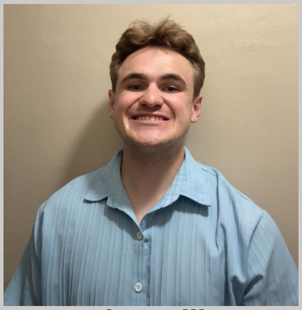
Camden Millheiser, Jessica Lange & Hanna Politte

Introduction:
Israel has developed one of the most advanced wastewater reuse systems in the world, driven largely by the country's natural water scarcity. With a semi-arid climate and rapidly growing population, Israel was compelled to treat wastewater not as waste, but as a critical resource (U.S. Environmental Protection Agency, 2023). Today, the country recycles approximately 87–90% of its wastewater, setting a global benchmark for water reuse (U.S. Environmental Protection Agency, 2023). This system operates through a highly coordinated national infrastructure that integrates municipal wastewater collection, advanced treatment facilities, and large-scale distribution networks. After initial treatment at regional plants, wastewater undergoes further purification (most notably through systems such as the Shafdan Wastewater Treatment Plant) before being transported through a centralized pipeline network for agricultural use, particularly in the Negev Desert (Mekorot, n.d.). This closed-loop system conserves freshwater for domestic consumption while ensuring a reliable, year-round supply for irrigation.

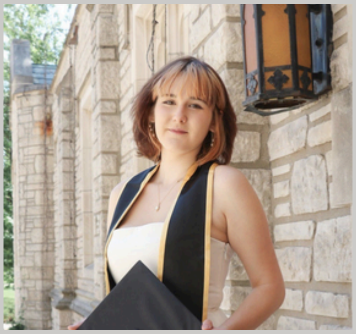
While Israel's success demonstrates how large-scale wastewater reuse can be effectively integrated into national infrastructure, it also raises critical questions; for example, why has the United States not implemented similar systems at scale? The U.S., despite having comparable technological capabilities, while engaging in wastewater reuse, does so only at limited and regionally fragmented scales (U.S. Environmental Protection Agency, n.d.). This limited adoption is not due to a lack of innovation, but rather fundamental differences in how water is governed, managed, and perceived culturally (OECD, 2015; Smith et al., 2018).

Unlike Israel's centralized and coordinated system, water management in the U.S. is highly fragmented across federal, state, and local levels, limiting the ability to implement unified, long-term strategies. This governance fragmentation can be seen by looking into the structure of how water in the U.S. gets delivered. The EPA notes that about 90% of the population gets their drinking water from about 50,000 independently regulated public water systems known as community water systems (U.S. Environmental Protection Agency, 2026a). This number of independent and currently uncoordinated systems would make the implementation of a nationwide system like that of Israel's a very tall task. Israel is well known for its long-term water planning strategies, including the National Long-term Master Plan for the Water Sector through 2050 (OECD, 2021). In the U.S., with its decentralized, dependent sourcing, the ability to coordinate long-term planning and implement large-scale infrastructure strategies across the country is

About the Authors



Camden Millheiser
I graduated from the University of Missouri with a Bachelor of Science in Biological Sciences. Originally from the St. Louis area, I developed interests in biology, history, archaeology, and global agriculture during my time at Mizzou. I currently work as a chemist at Trilogy Laboratories, where I perform analytical testing in a laboratory setting, and I look forward to continuing a career in scientific research and laboratory science.



Jessica Lange
Jessica Lange graduated from the University of Missouri in May 2026 with a Bachelor of Science in Biology. Following graduation, she began working as a phlebotomist in a hospital, to expand her clinical experience while caring for patients. She plans to apply to medical school next year as she continues pursuing a career as a physician.

limited. There are some federal agencies such as the U.S. Environmental Protection Agency that promote water reuse through initiatives like the Water Reuse Action Plan, though participation is mostly voluntary and implementation is left to individual states and municipalities (U.S. Environmental Protection Agency, 2026b). Because of this regulatory inconsistency and lack of coordination, significant gaps in what could otherwise be a cohesive national system become difficult to avoid (OECD, 2015). This lack of national coordination has some major consequences. As already noted, Israel reuses approximately 87 percent of its wastewater; in contrast the U.S. only reuses about 6 percent of its wastewater (U.S. Environmental Protection Agency, n.d.). As the U.S. is not a technologically limited nation in comparison to Israel, this dramatic difference in water reuse is not due to technological limitations, rather it is the inability to implement reuse systems at a national scale. The fragmentation of water systems in the U.S. is only one part of the problem, as deeper challenges related to infrastructure design and public perception also contribute to the limited adoption of wastewater reuse systems in the U.S. (OECD, 2015; Smith et al., 2018; Virginia Water Resources Research Center, 2024).

This paper argues that despite having the technological capacity to implement large-scale wastewater reuse, the U.S. has not done so due to three primary barriers: 1) fragmented governance structures; 2) infrastructure systems designed for disposal rather than reuse; and 3) cultural resistance driven by public perception. By examining these differences, this analysis will show that the primary challenge facing the U.S. is not technological, but institutional and societal.

Barrier 1: Fragmented Governance in the United States

In terms of trying to replicate the system that Israel has in place in any capacity, the fragmented structure of the U.S. water operations poses significant challenges for scaling water reuse technologies. In contrast to Israel's nationally coordinated approach where water resources are managed through a national water-sector planning framework (OECD, 2021), the U.S. treats water as a regional responsibility shaped by state, local, and federal institutions (US Water Alliance, 2018). One must understand that this is just how the U.S. has been doing things since the inception of the country, and water isn't the only resource that is treated as something that can be managed at different levels and by differing entities. According to the OECD (2015), decentralized water governance systems often struggle to align policies and investments across jurisdictions, limiting the ability to implement large-scale, coordinated solutions. This decentralization represents a key to explaining why the U.S., despite having the technological capacity for advanced treatment and reuse, has not approached wastewater reuse at the scale seen in Israel.

Political factors further reinforce these structural limitations. In Israel, water scarcity has long been treated as a national planning priority, reflected in the country's National Long-term Master Plan for the Water Sector through 2050, which defined Israel's vision, goals, and policies for future water management (OECD, 2021). Over time, this national focus developed into coordinated water policy, long-term infrastructure investment, and pricing mechanisms intended to support conservation and cost recovery (OECD, 2023). In contrast, the U.S. has not historically been a water scarce nation, even though water availability has become a rising concern in many western communities and rural areas (Anderson & Woosley, 2005). In the U.S., there has historically been less national urgency to manage water scarcity aggressively because there were fewer water constraints at the national level. This lower level of national urgencyled to more permissive water policies over time in the U.S. that are often influenced by state and local priorities rather than one coordinated national strategy (World Bank, 2017; U.S. Environmental Protection Agency, 2020). In addition, water is often undervalued in developed countries, including the U.S., with pricing systems that fail to incentivize conservation or investment in reuse technologies (U.S. Environmental Protection Agency, 2020). The U.S. has historically experienced few water constraints at a national level, reducing the urgency to adopt large-scale reuse strategies (World Bank, 2017).

It is clear that the lack of urgency lies within the major differences in water scarcity between the two nations. As the World Bank (2017) notes, countries facing severe resource constraints are more likely to adopt aggressive management strategies, while resource-rich nations often delay such investments. Many western U.S. states are currently experiencing or have recently experienced drought conditions, including California, Arizona, Colorado, Nevada, and New Mexico (National Integrated Drought Information System, 2025). Climate change has also intensified drought conditions in the Southwest by increasing evaporation and drying soils, with Drought.gov reporting that human-caused climate change contributed to about 42% of the region's soil moisture deficit since 2000 (National Integrated Drought Information System, n.d.). California is however leading a change in perception and action in the waterfront: in 2014, former Governor Jerry Brown and Israeli Prime Minister Benjamin Netanyahu signed an agreement to expand the cooperation between California and Israel (Office of Governor Edmund G. Brown Jr., 2014). This California-Israel agreement laid the groundwork for projects related to water scarcity, water conservation, and different kinds of agricultural technology. California shows that the U.S. isn't completely disconnected from Israeli water innovation. However, it also illustrates that these efforts are taking place mostly at the state and regional levels instead of through one coordinated national system.

Barrier 2: Infrastructure and Path Dependency

While the U.S. has the resources to implement advanced wastewater recycling systems, structural, political, and cultural barriers - rather than technological limitations - are the primary obstacles preventing adoption at the scale seen in Israel. The structural barriers are rooted in the historical development of sewer systems, treatment plants, and water distribution networks designed to remove waste, not recover it (Virginia Water Resources Research Center, 2024). This disposal-oriented design presents a broader infrastructural challenge, where systems prioritize disposal efficiency rather than circular reuse.

The path dependency of pipes created in the 19th and 20th-century creates the primary infrastructure design issue that prevents simpler implementation of wastewater reuse systems. “The Washington Post recently reported that the average age of a pipe in D.C. is 77 years, but a great many were laid in the 19th century. Sewers are even older” (Cohen, 2012). Early urban sanitation systems emerged in response to public health crises caused by unmanaged waste in the expansion of cities. “Many working-class families are compelled to reside in poorly ventilated, damp, and unsanitary dwellings with minimal access to clean water or proper sewage disposal. These circumstances have facilitated the rapid spread of infectious diseases, which has catastrophic consequences” (Vaishali & Boopathy, 2024). The introduction of indoor plumbing led to reduced crises, and sewer systems were rapidly built to transport the waste away from populated areas. Most cities adopted a combined or separate sewer system, determined by whether stormwater runoff flowed in the same pipe as sewage. The first systems discharged sewage directly into nearby waterways, often without treatment. The ‘collect and discharge’ model became the foundation for shaping modern water management practices in the U.S.

The infrastructure of waste removal did not change until the Clean Water Act of 1972: “The CWA prohibits pollution discharges into navigable, fishable, and swimming waters, which requires significant water treatment to increase effluent value and usage” (Kandou, 2023). Yet, the core purpose of the system remained unchanged: safe disposal. By the time the Clean Water Act was implemented, nearly all urban wastewater was treated, but was primarily disposed of into rivers, lakes, and oceans. The foundation of the modern U.S. infrastructure is to collect, treat, and discharge. This collect-treat-discharge model creates a one-way flow of water management that prioritizes disposal over circularity, which disrupts the potential for utilizing existing systems.

In contrast, Israel demonstrates how infrastructure can be reoriented towards integration rather than separation. Israel's water system operates as an interconnected network of desalination plants, wastewater treatment facilities, and natural water sources. “There is a major pipe and small pipes and smaller and smaller and smaller. And all the resources are connected to this pipe, including of course, all the desalination factories” (Water Resources Podcast, n.d.). The system is linked through the national water carrier and redistributes water across the country, functioning like an energy grid optimized for real-time decision-making. The National Water Carrier is a centralized pipeline system that transports water across Israel, which has allowed for advanced, coordinated distribution and integration of recycled and desalinated water. “So it's nice that you have this national water carrier then to allow you to transport water throughout Israel” (Water Resources Podcast, n.d.). The level of integration highlights the importance of infrastructure design for the scaling of reuse.

The linear model of water treatment used in the U.S. would require the implementation of a new distribution system to convert wastewater to reusable water. Most of the U.S. water systems consist of pipes that were primarily installed between 1950 and 1980 during the rapid expansion of urban areas: “Ductile iron pipes were introduced in the 1950s, a time of rapid population growth, and were marketed as an improvement over their cast-iron predecessors” (Cohen, 2012). The transition to a reuse-oriented system would require large-scale capital investments and coordinated planning across multiple sectors. This large-scale infrastructure investment is already evident in existing U.S. projects. For example, in Richmond Hill, Georgia, the construction of the Sterling Creek wastewater reuse facility in 2016 cost approximately $25 million, making it the largest single infrastructure expenditure in the city’s history (U.S. Environmental Protection Agency, 2025). Because of the high upfront costs and disruptions many cities are hesitant to pursue reuse projects. In Israel, the government overcame these barriers with large-scale investment and centralized planning. For example, the development of the National Water Carrier enables water to be transported across regions and integrated with innovations, such as desalination and recycled wastewater (Water Resources Podcast, n.d.). The centralized system reduces distribution costs and efficiently incorporates new water sources, enabling long-term flexibility and reuse.

The structural paradox of the U.S. system is the presence of unplanned water reuse. Treated wastewater is discharged into rivers and reused downstream. Many U.S. communities already rely on water that contains a majority of upstream effluent: “Some drinking water treatment plants use waters from which a large fraction originated as wastewater effluent from upstream communities, especially under low-flow conditions” (National Research Council, 2012). However, reuse occurs without intentional infrastructure, and the level of treatment is lower than planned reuse projects. Ray et al. (2005) explain that some drinking water supplies utilize streams that “might have been compromised in their quality due to the discharge of wastewater effluents or other waste streams. The system currently recycles water indirectly, but lacks infrastructure to do so efficiently, safely, and transparently.

The U.S. faces significant structural barriers to wastewater reuse rooted in its historical infrastructure. Sewer systems, treatment plants, and distribution networks were designed to move water away from cities instead of circulating within them. Overcoming these barriers would not only require updating the current system but also a fundamental reconfiguration of the water system to integrate a circular water management model. Israel’s system demonstrates that integration of infrastructure is a long-term investment that reduces dependency on natural resources: “Wastewater is a major source of the water being used for irrigation in Israel, actually, about 60% of the overall water being used for irrigation is from treated wastewater” (Water Resources Podcast, n.d.). Ultimately, the contrast between the U.S. and Israel underscores that the primary challenge is not the availability of technology, but the willingness to redesign infrastructure to support an integrated, circular water system.

Barrier 3: Public Perception and the “Yuck Factor”

On top of structural and political constraints, public opinion towards water reuse certainly has an impact on capital investment into adoption of large-scale water reuse strategies in the U.S. One major example of this public resistance is the ‘yuck factor,’ which refers to the psychological disgust associated with recycled wastewater, has become one of the main roadblocks standing in the way of support for reuse projects; occurring even when the technology has been proven to be both safe and effective (Ormerod, 2019). This concern is not just a generalized assumption, but is supported by research. Studies have shown that perceived health risks and the “yuck factor” are some of the most influential factors in terms of whether or not the public is willing to accept recycled water or not (Smith et al., 2018). This research bolsters the idea that resistance to wastewater reuse is driven as much by public perception as it is by policy or national infrastructure.

This public perception barrier brings us back to one of the most glaring contrasts between the two nations being compared here: unlike Israel, where water scarcity has created an entire culture of conservation and has normalized the use of treated wastewater, the U.S. has not approached the same level of public acceptance. “In addition to growing water demands, the further adoption of water reuse will be affected by a variety of issues, including water rights, environmental concerns, cost, and public acceptance” (National Research Council, 2012). The lack of public trust in the U.S. influences policy decisions and reduces political willingness to invest in reuse infrastructure, reinforcing existing institutional barriers. It thus becomes less about whether the technology works, and more about whether people are willing to accept it, which as of right now, it is clear that public acceptance remains limited in the U.S. Ultimately, even with viable technology in the U.S., the success depends on public trust and institutional support, an issue that extends beyond national borders.

Conclusions:

Global research suggests that the underutilization of wastewater reuse is not because of technological limitations, but rather institutional, public opinion, and policy barriers (Qadir et al., 2010). The U.S. is just one of many nations reflecting hesitation to wastewater reuse adoption that is centered around governance fragmentation, inconsistent policy frameworks, and a lack of political and financial incentives. Taken together, these structural, political, and cultural factors demonstrate that the primary barriers to wastewater reuse in the U.S., as well as other countries, are institutional rather than technological.

Once all these barriers are taken into consideration, a rather clear pattern begins to emerge: the challenge facing the U.S. isn’t just a matter of isolated policy mishaps or infrastructure that is past its due date, rather a much broader lack of alignment between governance, infrastructure, and public perception. Each of these barriers have an impact on one another, making it that much more difficult to implement large-scale solutions even when the technology to do so already exists. Unlike Israel, where water management operates as a unified national priority, the U.S. approaches water as a fragmented and regionally managed source. This fragmented approach is the main underlying disconnect that is preventing the nation from scaling solutions that have already been proven to be both efficient and successful.

Israel’s success in wastewater reuse shows that large-scale water recycling is not only possible, but very effective when the needed support is provided by coordinated systems and national priorities. However, the U.S. displays how structural fragmentation, political decision-making, cultural perceptions, and infrastructure design can collectively limit the adoption of even the most advanced technologies. Even with technology that is needed to scale wastewater reuse at high levels already existing, the lack of alignment across governance, policy, and the general acceptance of the public is what continues to prevent implementation of these systems in the U.S. This implementation challenge is a multifaceted issue and it is going to take a lot more than technological investment to get the ball rolling for wastewater reuse strategies to get serious traction. It will take a complete shift in how water is perceived, valued, and managed in the U.S. Until some of these realities change, wastewater reuse will likely remain underutilized in the U.S., despite its proven potential as a sustainable solution for ever increasing water demands.

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Impact of Drip Irrigation on Plant Root Development and Biotic and Abiotic Aspects of Soil

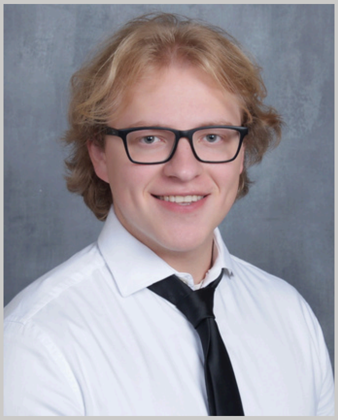
Dominykas Vaiciulis, Theo Krummel & Cole Arnold

Introduction

Drip irrigation is widely used in water scarce agricultural systems and has been described as the “dominant mode of micro-irrigation in India” (Bhattacharya et al., 2024). Touted for its water use efficiency, optimizing crop yield, and overall sustainability that makes growing plants in the desert a feasible project, drip irrigation is often considered a superior irrigation method to others (Mebrahtu & Tamiru, 2018). In a study comparing furrow versus drip irrigation, it was found that for certain crops, drip irrigation had a yield four times that of furrow irrigation (Al-Haddad, 2014). Furrow irrigation involves narrow, half-pipe like troughs that run alongside crops. These troughs are strategically placed to cover the entire field of crops. The downside is that water percolates too deep in the soil or evaporates (Al-Haddad, 2014). Crops also received inconsistent watering and showed signs of strain during boom and bust cycles of drought, with a study highlighting that crop growth is negatively impacted with variable water cycles (Cousins, 2020). Drip irrigation, therefore, has become renowned for supplying minimal and consistent water directly to the root zone of crops to combat these issues, while also maximizing crop yields (Al-Haddad, 2014). However, the belief that drip irrigation is an engineering success and saves water is accurate, but incomplete. Biological factors that arise as a consequence of the altered environment from drip irrigation are at present largely unappreciated. Drip irrigation creates a wetting zone around the roots, which is the intended purpose and the primary mechanism that creates the incredible water efficiency in this irrigation system. The wetting zone is consistent and its pattern is able to be accurately modeled and predicted in simulation (Liu, 2015).

In natural environments, plants are exposed to variable sources of water, such as rainfall. Plants have evolved resilience and become adaptive in response to the variability of natural water availability. Drip irrigation eliminates this variability and provides the constant wetting zone as discussed. This consistency includes a tradeoff. Although it is sustainable watering, it is a reduction in the heterogeneity of the natural environment in which the plants and other biological organisms evolved. This concept is supported by the semi-arid Chilean shrub, which shows that exposure to naturally variable water promotes adaptive traits that become diminished under consistent watering conditions (Lázaro-Nogal et al., 2015).

About the Author



Dominykas Vaiciulis

Dominykas Vaiciulis is a graduate of the University of Missouri - Columbia, where he earned his Bachelor of Science in Biological Sciences, a minor in Chemistry, and a certificate in Neuroscience. His curiosity about plant physiology led him to investigate how biological systems adapt to environmental change, particularly the effects of irrigation practices. Beyond plant physiology, Dominykas’ interests include clinical medicine and improving healthcare through science communication. He plans to pursue a career as a physician while continuing to contribute to scientific research.

This review on drip irrigation was completed in collaboration with fellow undergraduates Theo Krummel and Cole Arnold.

This review examines how the consistent watering provided by drip irrigation reshapes plant root architecture, soil microbiome, and plant resilience, providing evidence that while drip irrigation substantially increases water use efficiency and crop productivity, it does so with potential tradeoffs in ecological resilience that must be considered when implementing this system.

Wetting Zones as a Selective Pressure

Lazarovitch (2007) found that the shape and size of the wetted area was not correlated with soil type or time, lowering the bounds of which the predictability of wetting zone consistency can be applied. The local wetted zone also creates environments where certain microbes thrive better than others, particularly microbes that are anaerobic and have greater survivability in these consistently moist, oxygen limited environments (Das, 2025). Over time, certain microbes named plant-growth-promoting microbes (PGPMs) have become an active member of supporting plant growth via regulation of soil nutrients and microbiome (Das, 2025). This is an evolutionary example of how shaping of the microbiome in the soil that crops are grown in has altered the fitness of a crop (Ansabayeva et al., 2025). In a consistent and predictable wetting zone that alters root structure and microbiome of the soil, drip irrigation is an active selective pressure on crop fitness. It not only enhances sustainability, but can also be used as an evolutionary tool with the way that it manipulates the ecological dynamics of agriculture. This introduces a key tradeoff between efficiency versus resilience. Delivery systems for irrigating crops may be optimized for crop yield, but a reduction in the ability for a plant to respond to other environmental stressors outside of water could lead to larger, ecological effects.

Root Architecture Under Drip Irrigation

One effect that the wetted area resulting from drip irrigation can have on roots is the depth to which the roots penetrate the soil. Along with affecting the root length, drip irrigation has a very distinct effect on the number of roots and mass of root tissue (Ma, et al., 2013). Roots may stay at a shallower depth around the wetted area and continue to accumulate new lateral roots and mass in this area when compared to non-drip irrigated roots. In a study done on Jujube trees, a type of Chinese date tree, the maximum root depth of drip irrigated trees that had been growing for 12 years was 5 meters. In contrast, the maximum root depth for a stand of 12 year old trees which had not received drip irrigation was 10 meters (Ma et al., 2013). This study was conducted in Mizhi County, Shaanxi Province, an arid region where the average precipitation for a year during the course of the research was 33.3mm. The maximum rain penetration was 2 meters into the soil (Ma et al., 2013). Non drip irrigated trees are adapted to a range of environments and so deep root penetration helps with drought tolerance. This deep root penetration allows for the trees to find water deep in the ground to supplement the sparse instances of precipitation (Ma et al., 2013). Therefore the fact that the drip irrigated trees had half the root depth is a significant difference and shows that the consistent wetted zone affects plant anatomy dramatically.

Root growth and architecture differences were also seen in winter wheat (Ma et al., 2022). When wheat was irrigated and fertilized by flooding and surface application root depth extended farther than surface drip irrigation and subsurface drip irrigation. However, the density of roots was higher at a shallower depth for flood irrigated wheat. Dissimilar to the previously mentioned Jujubee tree, winter wheat is not adapted to send down deep roots to find water during periods of drought (Ma et al., 2022). Drip irrigated wheat had more root density at depths of 40-80cm than surface drip irrigated wheat. Ma and colleagues (2022) found that the drip irrigated wheat also had significantly higher root density than flood irrigated wheat at the latest growth stages. These differences in depth and density also affected root activity, measured as water uptake over time. Between 0-20 cm of depth subsurface irrigated wheat had the lowest root activity of the three irrigation methods; however, after 20cm, subsurface irrigated wheat has higher root activity than surface drip irrigated and surface flood irrigated wheat. Both arid- and non-arid-adapted plants have significant changes to root growth and architecture as a result of the type of irrigation used. Though in both cases the wetted area does have a significant impact on the density and depth of the roots (Ma et al., 2022).

In a study done on apple trees drip irrigation also produced a difference in the root growth and architecture. Though the amount of water applied had the greatest effect on the root structure (Sokalska et al., 2009), the presence of the drip irrigation alone was not the sole determining factor. Three groups of apple trees growing in a climate that received an average total precipitation of 372mm were grown receiving no drip irrigation, intense drip irrigation, and economical drip irrigation. The drip irrigation was also applied to only the north side of the trees. The investigators found that under intense irrigation the tree roots spread the most asymmetrically with more roots growing on the south side of the tree. And while roots were found at all depths across the three treatments, only the control group had roots with a diameter greater than 3mm at a depth of 100cm (Sokalska et al., 2009). These results showed that depending on the level of irrigation roots will not only congregate around the wetted area but at high levels of irrigation will also disproportionately branch out into the non-irrigated side of the tree.

Soil Microbiomes Under Drip Irrigation

Another notable effect of drip irrigation is a change in composition of soil (Wang et al., 2023). Along with the use of fertilizers, soil microbiomes are important for sustaining nutrient levels that promote plant growth. Drip irrigation appears to act as a selective pressure on the microbes present in the soil (Wang et al., 2024). Abiotic factors like salinity and heavy metal content are also important to consider for plant health and human health (Guo et al., 2023; Lu et al., 2016), thus drip irrigation not only affects the structure of the plant and the soil microbiome, but also the composition of the soil (Guo et al., 2023).

Drip irrigation has been found to have a strong impact on the microbe biodiversity of the soil environment in which it is operating (Wang et al., 2023; Zhang et al., 2023). Whether impact is beneficial or detrimental varies based on several factors. For example, drip irrigation systems that utilize reclaimed water were found to lead to an increase in soil salinity within the first 0-60cm layer compared with tap water (Qiu et al., 2022). Higher salinity is a major concern in agriculture because salt accumulation can degrade soil conditions and interfere with nutrient transformations important for crop production (Guo et al., 2023). Some drip irrigation systems utilize a water solution that consists of reclaimed water with a low content of chlorine introduced as a maintenance/disinfection step (Song et al., 2019), and it was found that systems that use this practice reduced microbial growth and reproduction in the soil environment (Qiu et al., 2022). However, there were cases in which drip irrigation had net positive effects on the microbial environment in which it was functioning (Wang et al., 2024). In this case, it was observed that the timing/amount of irrigation changed the composition of beneficial bacteria present. An increase in irrigation during the period from the big trumpet stage to tasseling (crop growth stage intervals of maize plants) significantly increased the Chao index (richness of soil bacteria index) of soil bacteria by 2.95% relative to the control (Wang et al., 2024). This change in microbe diversity led to an increase in nutrient availability, especially for potassium. It should be noted that during other timing intervals, some microbial groups were eliminated by the treatments and that the favorable response only occurred during the one timing period. These results are likely only significant and replicable in these specific plants (maize) and more studies will need to be done to determine the specific intervals to water plants for beneficial microbe growth in other crops. In a separate study, it was observed that soil irrigated with saline water over a period of 11 years had major changes in bacteria composition, as well as salinity, soil water content, and nutrients (Guo et al., 2023). Over time gene expression in the bacteria also changed: expression of genes associated with nitrogen fixation, denitrification, and dissimilatory nitrate reduction increased, while genes associated with nitrate/nitrite transport and nitrification decreased. These changes made nitrogen availability less favorable for the plant overall under saline irrigation, because nitrate declined and nitrification was suppressed, even though N fixation was increased (Guo et al., 2023). Together these documented changes in microbe diversity and function provide strong evidence that drip irrigation systems can function as environmental selective pressures in the microecosystem in which they are applied.

Several studies where either reclaimed water or saline water was employed, found that salination of the soil increased. (Wang et al., 2023; Guo et al., 2023; Lu et al., 2016). Reclaimed water is commonly used in agriculture to preserve natural freshwater, and also for its higher nitrogen content, but as we have seen can lead to changes in the soil over long periods of time (Guo et al., 2023).

Soil salinity as previously stated in this paper can be a major concern, but drip irrigation actually has a much higher desalination rate than regular flood irrigation (18.46%-22.94% vs 5.32% respectively) (Wang et al., 2023). Drip irrigation also keeps soil water distribution (and therefore salt and nutrient distribution) much more uniform than flood irrigation, which in comparison over time damages soil structure and leads to uneven water infiltration (Wang et al., 2023). This means that drip irrigation makes saline water a viable option for agriculture in areas where there are no other options, so long as the proper measures are taken to maintain the soil.

Drip irrigation also has been found to reduce stress on plants that are grown in soil contaminated with heavy metals (Zhang et al., 2023). In a study of soybeans with drip irrigation and flood irrigation in soil with high heavy metal content, it was found that drip irrigation reduced Cd, Pb, and Cr(VI) concentrations in the root zone by 34.88%, 31.35%, and 34.20% respectively (Zhang et al., 2023). This was good for the soil, but it was found that higher amounts of heavy metals had ended up inside of the soybean plant. This wasn't purely a negative though, upon examination Zhang et al. (2023) found that the majority of the metals stayed in the roots with low concentrations ending up in the seeds of the plant.

Conclusions

Here we show that there is much more to consider than just crop production and water efficiency when utilizing drip irrigation. Over time, major changes to microbial biodiversity and soil composition (including salinity of the soil, and heavy metal accumulation) can be affected with use of drip irrigation. Drip irrigation is a key technological advance in agriculture (Wu et al., 2020). Without drip irrigation sustained high production agriculture in arid areas may not be possible. At the very least it would not be as efficient and would take much longer to establish and become productive and profitable. But drip irrigation has drawbacks that may be overlooked due to the success it has provided in water use efficiency and crop yields. Substantial changes have been documented to occur to the structure and function of plants roots when drip irrigation is used. Adding complexity to this issue, these changes vary among different plant types, but they may not necessarily harm the plant if it can still grow under conditions where it otherwise could not survive without drip irrigation. If methods change at a crop field or orchard it is important to keep in mind that the roots of these plants have previously grown under different specific conditions, and if these conditions are not maintained the plant may fail to produce to the same level, or produce at all. Drip irrigation also creates a selective pressure on the soil microbiome and the microbes present in the soil have a big impact on the health and productivity of the plant.

These effects don't occur in isolation, rather they're all part of an interconnected system in which drip irrigation affects the growth, and development of plants. The formation of stabilized wetting zones concentrates water and nutrients which affects the overall density and architecture of the root structure (Ma et al., 2022). The same wetting zones provide sizable influence on the soil microbiome, which is further fortified due to the clustered, shallow roots. In turn, nutrient cycling is impacted by these microbial and plant changes (Lattacher et al., 2025). What this means for environmental resilience in plants under drip irrigation conditions is the formation of a feedback loop as a result of the co-adaptation between root systems and soil microbiome. As a result, this dependence, which presumably no longer tolerates non-drip irrigation watering patterns, is rendered vulnerable to environmental challenges.

Ultimately, drip irrigation should not be viewed solely as an efficient water delivery system, but also as a selective pressure that reshapes plant root systems and the microbiomes of the soil the plant occupies. While the efficiency and sustainability of drip irrigation is unparalleled (Mebrahtu & Tamiru, 2018), it comes with this hidden tradeoff: Reduced biodiversity and ecological resilience. Acknowledging these hidden costs of efficiency is crucial towards making better environmental decisions with furthering agricultural innovation.

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Resource Efficiency and Plant Productivity in Vertical Farming: A Comparative Analysis of Hydroponic and Aeroponic Systems

Ava Nickell, Cody Vondera & Vanessa Malherek

Spring Forum Abstract Award Winner

Introduction

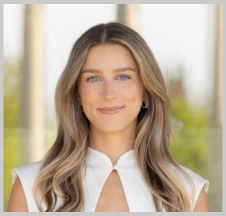
As environmental and geographical constraints continue to affect traditional agriculture, vertical farming offers an alternative solution for sustainable food production. Vertical farming is a controlled-environment agricultural practice that involves cultivating crops using hydroponic, aeroponic, or other soilless systems (Ling & Atland, 2025). This cultivation approach provides several advantages that are difficult to consistently achieve through traditional agricultural practices: first, the crops produced by traditional farming are limited by geography and seasonal changes; vertical indoor farming allows for the growth of regional and seasonal crops year-round, anywhere a controlled environment can be established (Ling & Atland, 2025). Second, vertical farming uses less land than traditional agriculture, as crops are grown indoors, often in vertically stacked layers, rather than horizontally across large fields (Ling & Atland, 2025). This method of farming allows for a greater crop yield per unit area. For example, a vertical farming greenhouse can produce 50–100 times greater yield per square foot than traditional agriculture due to its high-density, year-round production capacity (Funk, 2025). Third, vertically farmed crops can also often be grown without pesticides (Ling & Atland, 2025).

Among the most widely used soilless cultivation methods in vertical farming are hydroponic and aeroponic systems, both of which are designed to optimize resource delivery and plant productivity under controlled environmental conditions. Hydroponic systems utilize a nutrient-rich water solution as a root environment rather than soil, whereas aeroponic systems suspend plant roots in air and deliver nutrients through a fine nutrient-rich mist (Sihag et al., 2025). This paper evaluates how differences in water potential and nutrient delivery between hydroponic and aeroponic systems alter plant physiological processes, including photosynthetic efficiency, plant growth rate, and energy-use tradeoffs within vertical farming systems.

Principles of Plant Physiology

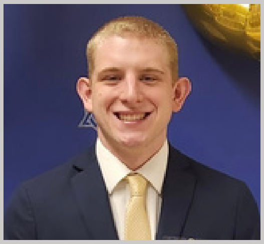
To understand these plant growth systems, we first need to understand the physiological mechanisms of plants that determine growth, productivity, and resource efficiency. A key process governing plant function is the movement of water, regulated by differences in water potential. Water potential refers to the free energy of water and determines the direction and flow rate of water movement within the soil–plant–atmosphere continuum (De Swaef et al., 2022). This movement is driven by gradients created through transpiration at the leaf surface, generating a pull of water through the plant (Trimble, 2022).

About the Authors



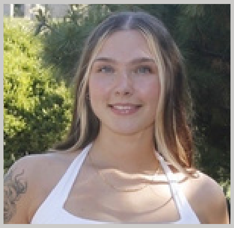
Ava Nickell

I was born and raised in Leawood, Kansas, and came to the University of Missouri as a Biology major. Throughout college, I expanded my interest in health care through a variety of clinical and educational experiences and through my work in undergraduate research in neurophysiology. After graduation, I look forward to continuing my education through medical school and pursuing a career as a physician.



Cody Vondera

I was born and raised in Washington, Missouri. While attending Mizzou I pursued a degree in Biological Sciences and established a passion for dentistry. In my time at Mizzou, I enjoyed some new hobbies like running, camping, and hiking while also volunteering in the Big Brothers and Big Sisters program. After graduation, I plan to attend the UMKC Dental School.



Vanessa Malherek

I was born in Illinois and raised in Columbia, Missouri. I am majoring in biological sciences and have always been fascinated with human anatomy. After graduation, I plan to apply to pathology assistant school and further my knowledge in anatomy and pathology. My goal is to get a master's degree and work in a medical examiner's office.

Closely related to water movement is the transport of nutrients. The xylem transports water and dissolved ions from the roots upwards through the plant, while the phloem transports metabolites in solution to developing roots, leaves, and fruits (Lopez & Barclay, 2015). These processes ultimately support photosynthesis, the mechanism by which absorbed solar energy is converted into chemical bond energy in the form of carbohydrates (Johnson, 2016). The rate of photosynthesis is influenced by several environmental factors, including water availability, light intensity, carbon dioxide concentration, and temperature. The carbohydrate bond energy produced through photosynthesis is then used for growth, maintenance, and biomass accumulation (Weraduwage et al., 2015).

These physiological mechanisms lay the foundation of soilless agriculture systems used in vertical farming (Gurung et al., 2024). By monitoring and controlling water availability, nutrient concentrations, and environmental conditions, growers are able to directly influence plant functions at multiple levels to optimize growth conditions and resource-use efficiency, compared to traditional systems (Sihag et al., 2025). The ability to regulate these factors also reduces variability in plant production, allowing for more predictable outcomes in crop yield and quality (Gurung et al., 2024). These insights have led to the development of the modern systems seen in vertical agriculture today.

Hydroponics

Hydroponics, which means "water labor" in Greek, is an example of a soilless plant cultivation system commonly used in vertical farming (Gurung et al., 2024). This method relies on a nutrient-rich water solution to deliver essential ions directly to plant roots, eliminating the need for soil. Instead, plants are supported by inert growing media such as perlite, rockwool, or clay pellets, which provide structural stability while allowing the circulating solution to supply nutrients efficiently (Rajaseger et al., 2023). In these systems, water is continuously recirculated, maintaining adequate oxygen levels while delivering nutrients indirectly to the roots (Sihag et al., 2025). Hydroponic systems offer a range of advantages, particularly in optimizing resource use and spatial efficiency. One of the most significant benefits is water conservation, as hydroponic techniques have been shown to reduce water usage by up to 90% compared to traditional farming methods (Rajaseger et al., 2023). In addition to reducing water use, hydroponic systems have been shown to increase crop yields by approximately 20-25% compared to traditional soil-based agriculture, with some studies reporting even greater increases depending on crop type and growing conditions (Rajaseger et al., 2023; Sihag et al., 2025). Sihag and colleagues (2025) describe several additional benefits of hydroponic farming beyond water conservation and nutrient delivery. These include: improved pest control through controlled growing conditions, enhanced produce quality and flavor resulting from precise nutrient delivery, reduced water loss associated with evaporation and runoff through nutrient recirculation, and decreased exposure to soil-borne diseases and certain pest-related risks.

However, despite these benefits, hydroponic systems are not without challenges. Initial setup costs can be high, and many systems require intensive management, including frequent monitoring and maintenance (Rajaseger et al., 2023; Gurung et al., 2024). Although water is recirculated, hydroponic systems still utilize a moderate amount of water compared to newer technologies, which may present sustainability concerns (Sihag et al., 2025).

Aeroponics

Building on the principles of hydroponics, aeroponics has emerged as an innovative alternative designed to further enhance efficiency and resource conservation (Lakhiar et al., 2024). While similar in concept to hydroponics, aeroponics eliminates the use of both soil and inert growing media, instead suspending plant roots in air and supplying nutrients through a fine mist. This system helps reduce plant stress factors such as hypoxia, salt accumulation in the root zone, and mechanical resistance that can hinder root development (Tafesse et al., 2021). Water mist rich in nutrients is delivered directly to the exposed roots through precision-controlled nozzles or sprayers, allowing for highly efficient nutrient delivery (Sihag et al., 2025). One of the most significant advantages of aeroponic systems is the increased oxygen availability to plant roots. Because roots are suspended in air rather than submerged in water, they are exposed to higher oxygen concentrations, which enhances cellular respiration and supports greater energy production for growth (Tafesse et al., 2021). Another key strength of aeroponic systems is their ability to provide highly precise environmental regulation. In addition to maintaining consistent nutrient delivery, aeroponic systems allow for direct control of root-zone oxygen availability, pH, humidity, temperature, light exposure, and misting intervals (Gurung et al., 2024). This high level of control facilitates optimal growing conditions; improved oxygen availability and nutrient delivery in aeroponic systems can lead to enhanced plant growth and productivity compared to optimal hydroponic conditions (Tafesse et al., 2021; Sihag et al., 2025). This highlights a key tradeoff between systems, where hydroponics offers greater stability and scalability, while aeroponics prioritizes maximum resource efficiency and optimization of plant physiological performance (Sihag et al., 2025).

Compared to hydroponics, aeroponics uses significantly less water due to its misting and recycling mechanisms (Sihag et al., 2025; Lakhiar et al., 2024), while also providing greater oxygen exposure to plant roots. These factors not only accelerate plant growth, but also reduce disease susceptibility (Sihag et al., 2025), while maintaining the space efficiency necessary for vertical farming systems. In contrast, traditional soil-based and hydroponic systems are more susceptible to the spread of soil or water-borne pathogens, making the reduced disease transmission in aeroponics a key advantage for plant health (Sihag et al., 2025). Despite these advantages, aeroponics also presents notable challenges. First, the system relies on advanced technology that may make it more complex and potentially difficult for beginners to manage effectively. Second, the initial investment cost is typically higher than that of hydroponic systems due to the specialized equipment required for mist generation and environmental control (Sihag et al., 2025). When directly comparing hydroponic and aeroponic systems, aeroponics often demonstrates greater efficiency in water use, oxygen availability, and potential growth rates, while hydroponics remains more practical for large-scale implementation due to lower cost and system complexity (Sihag et al., 2025; Tafesse et al., 2021). This highlights an important tradeoff between maximum biological efficiency and real-world scalability, suggesting that the most effective system depends on the specific environmental and economic context.

Deployment of These Systems

Vertical hydroponic and aeroponic systems are frequently implemented in regions where traditional agricultural practices are limited or impractical due to environmental or geographic constraints (Ling & Atland, 2025). While several factors can contribute to suboptimal plant growth, traditional agricultural systems are often limited by seasonal variation in available sunlight. Each plant species has unique light requirements necessary for optimal growth and productivity (Mollick, 2025). Crops like tomatoes, peppers, and squash demand at least 6 hours of full-sun, while shade-tolerant leafy greens like kale and arugula manage with just three to four hours (Mollick, 2025). While these durations reflect the minimum light exposure necessary for plant growth, excessive exposure to full-sun conditions can also negatively affect growth in certain plant species. In addition to duration of light exposure, the light quality is also an important factor influencing optimal photosynthesis and plant growth. The quality of sunlight can be described by its spectrum (color) or wavelength of light, with different regions of the spectrum (wavelengths) producing different physiological effects within the plant. For instance, increasing the amount of blue light can result in more compact, stockier plants, while increasing red light intensity during flowering can enhance plant growth rates and crop yields (Don, 2025). Considering these two factors, exposure duration and spectral quality of the light, it's clear that traditional outdoor growing practices will not be equal in all places where sunlight serves as the sole light source.

LED Lighting in Vertical Farming

Vertical agriculture systems are not exempt from light conduction constraints, especially when located in indoor facilities that lack external light. To overcome these limitations and constraints, indoor facilities often incorporate light-emitting diodes (LEDs). Typical LED arrays used in vertical agriculture systems primarily supply photosynthetically active radiation (PAR) between 400 and 700 nm, which is optimally tuned to the absorptive properties of the plant photosynthetic machinery (Pereira & Gomes, 2025). Standard white-light LED bulbs have low PAR, limiting their ability to effectively support plant growth, while plants do not require all light wavelengths produced by the sun, making specialized LEDs that produce optimal PAR more energy efficient (Savage, 2026). LEDs also contribute to the water-efficient goals associated with implementing hydroponic and aeroponic systems; specifically, how the plant moves and utilizes the water. The process by which plants absorb water through their roots, transport it upward through their vascular tissues, and release it as water vapor through their stomata is called transpiration (Helmenstine, 2026). In traditional agricultural systems, limited sunlight exposure can reduce stomatal activity, thereby slowing water uptake and transport within the plant (Park et al., 2023). LED use aims to optimize the stomatal opening time to promote growth. One study specifically studied the effects of far-red light (between 700-800 nm) on stomatal activity in sweet basil plants (Park et al., 2023). It was found that basil plants had a larger stomatal aperture area when grown with added far-red light and thus had greater evapotranspiration (combined process of water evaporation from the soil and transpiration through the plant) rates, leading to increased plant height (Park et al., 2023). This study exemplifies how LED lighting can have predictable and dramatic effects on plant growth when used with precision.

While LED lighting provides many benefits in these systems, it does not come without costs (Pereira & Gomes, 2025). Implementing these LED systems often requires elaborate technologies to have the desired effect. Specialized sensors and timing systems are required to fully utilize the adjustable spectral and intensity properties of LED arrays in order to optimize plant growth and agricultural productivity (Pereira & Gomes, 2025). Additionally, there is an inherent increase in energy use for vertical agriculture systems due to the equipment necessary to create these controlled environments. For example, the energy needs of lettuce grown using controlled environment hydroponics systems were more than 80 times greater than conventional methods (Pereira & Gomes, 2025). These increased energy requirements can contribute to substantially higher production and supply-chain costs. One economic comparison estimated the delivered cost of saleable lettuce at approximately $7.82 per kilogram for vertically farmed lettuce, compared with $3.04 per kilogram for conventionally field-grown lettuce (Gargaro et al., 2023). Although vertical farming may reduce transportation distances and provide more consistent year-round production, its dependence on artificial lighting and environmental control can therefore limit its economic competitiveness.

Conclusions

Vertical farming systems, particularly hydroponic and aeroponic systems, represent a significant advancement toward more controlled and resource-efficient food production under environmental and geographic limitations (Gurung et al., 2024). By leveraging plant physiological principles such as water potential, nutrient transport, and photosynthesis, these systems enable highly controlled growth conditions that improve resource-use efficiency compared to traditional agriculture (Gurung et al., 2024). While hydroponic systems provide reliable nutrient delivery and water conservation, aeroponic systems enhance root-zone oxygen availability and resource-use efficiency, often resulting in faster growth rates and increased productivity (Rajaseger et al., 2023; Sihag et al., 2025; Tafesse et al., 2021). The integration of advanced LED lighting systems further allows growers to precisely regulate light spectrum and duration in order to optimize plant performance (Pereira & Gomes, 2025). However, the benefits of these systems are accompanied by significant tradeoffs, particularly in terms of high energy consumption and technological complexity (Pereira & Gomes, 2025). Ultimately, the future of vertical farming depends on improving energy efficiency while maintaining high productivity. Continued innovation in lighting, system design, and environmental control will be necessary to achieve truly sustainable vertical agriculture.

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Urban Agriculture in Review: Hydroponics, Aeroponics, Aquaponics

Skylar Griffith, Rhea Fowler & Matthew Mincemeyer

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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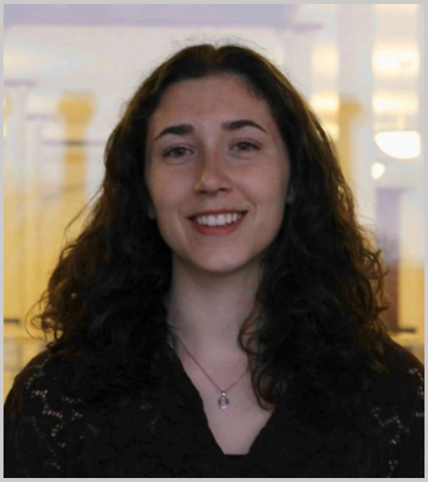

Skylar Griffith

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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