**Hydroponic Systems: Best Practices for Biosecurity, Disinfection and Pest Management**

**Abstract**

Hydroponics is a soilless farming which is revolutionizing agriculture by improving yield, space utilization and water efficiency. However, microbial contamination, biofilm development and pest infestation pose major threats to food security and system sustainability. In this review we researched about cleaning, disinfection and pest control techniques used in hydroponic farming. Most efficient disinfection is sodium hypochlorite (NaOCl) but we also present environmentally friendly alternatives like sodium percarbonate (SPC) and hydrogen peroxide (H2O₂). Preventing pests sustainably using integrated pest management (IPM) methodologies (e.g. physical barriers, biological controls). If hygiene techniques are properly followed through rigorous sanitization practices and adherence to food safety regulations for hydroponic systems. Future studies should focus on novel disinfection techniques to further enhance biosecurity. Hydroponic systems, however, rely on strict sanitization measures and must comply with food safety legislation to maintain their integrity.

**Keywords:**

Hygiene IPM, Hydroponic, Contamination, NaOCl, H₂O₂, Sustainable agriculture.

**1. Introduction**

Hydroponics is a ground-breaking agricultural technique that enables plants to thrive without soil, with the assistance of a precisely regulated water-based solution that provides vital nutrients. Due to its excellent effectiveness, sustainability and its ability to cultivate crops in urban or resource-limited areas, this method has become ubiquitous (Naresh et al., 2024). Unlike traditional soil-based farming, hydroponics avoids issues such as nutrient leaching, soil degradation and unchecked pest infestations, allowing for food production year-round, with higher yields and lower water use (Thakur et al., 2023). However, the high susceptibility of hydroponic systems to microbial contamination and pest infestation could threaten the quality of food and health of plants (Sela et al., 2023). Hydroponic farms can have pathogenic microorganisms including Salmonella, Escherichia coli and Listeria monocytogenes that can constitute a serious risk to the health of consumers when basic cleanliness practices are not strictly followed (Riggio et al., 2019; Dong & Feng, 2022).

Biofilm is one of the greatest challenges in hydroponic systems, with microbial populations adhering to the surfaces of systems (e.g., pipes, reservoirs and nutrient solution tanks) [18-20]. Biofilms protect bacteria against normal sanitization procedures. Research finds that several bacteria, such as *Pseudoxanthomonas mexicana* and *Corynebacterium tuberculostearicum*, help bad diseases colonize hydroponic nutrient solutions (Tham et al., 2024). These systems however are at much higher risk of rapid contamination spread than traditional farms when the water is continuously recirculated. Effective cleaning and disinfection are essential for preventing outbreaks and for meeting food safety regulations because those particles, combined with warm, nutrient-dense water, create an ideal environment for these microbes to grow.

Along with microbial contamination, hydroponic farming also has a similar infestation of pests. Airborne pests such as aphids, whiteflies and fungus gnats which can bring in plant diseases and interrupt growth even with hydroponic, soil-less systems that minimize soil-borne pests. Because traditional pesticides can lead to health risks and regulatory challenges when used in constrained circumstances, hydroponic farmers should take an intentional approach to pest management. Integrated pest management (IPM) approaches such as biological control, physical barriers and low-reliance substances are fundamental to reducing pest-related threats and promoting the safe and sustainable production of crops. Insects may be avoided as well as plant health offering protection may use air filtration, humidity control and optimized greenhouse conditions.

In addition to the regulatory aspect of food safety and legal compliance, hygiene in hydroponic farming aids in crop output and facilitates sustainable farming practices. Governments and food safety agencies regulate hydroponic by using controlled-environment farming through strict sanitization standards as guided by the Food Safety Modernization Act (FSMA) and Good Agricultural Practices (GAP). Such standards require proper sanitising, water quality testing, worker hygiene and cleaning schedules, among others. Forgetting to do so can have serious consequences simply to the fact you failed to properly sterilise the hydroponics system. This mandatory process involves the use of different eco-friendly disinfectants such as, peracetic acid (PAA), hydrogen peroxide (H2O₂) and sodium hypochlorite (NaOCl). Nevertheless, researchers are still trying to develop less expensive, non-toxic and eco-friendly sterilization treatments that can be widely applied in hydroponics systems.

Thus, attempting to minimize the risk of contamination, this review will address the importance of hygiene in hydroponic farming, discussing cleaning, disinfection and pest control practices. This guide to hydroponic system sanitation and how it can help ensure food sustainability and safety is underpinned by an exploration of best practice approaches, scientific advancements and regulatory frameworks. We further outline potential opportunities for new research insights and innovative technologies that can be explored for advancing hydroponic microbial management and enhancing the overall safety and efficiency of agriculture on a global scale.

**2. Basic Hygiene Practices for Growth Facilities & Hydroponics Labs**

Throughout the plants life cycle hydroponics growing units must maintain a certain level of cleanliness and sanitation to prevent contamination, a plant disease that can hinder growth and limit crop yield. Hydroponic systems are devoid of soil and therefore are particularly susceptible to microbial contamination like algae development and biofilm formation, since they rely solely on water-based fertilizer solutions (Tokunaga et al.,2024). Proper cleaning and sanitation reduce the chances of system constrictions and pathogen build up and also reduces the chances of nutrient imbalances to a large extent.

**2.1 Routine Maintenance & Cleaning**

A well-structured cleaning routine during one specific time on a daily basis is crucial to obtain a sanitary hydroponic system. In hydroponic farms, there is a necessity to take preventive action to stop the microbial contamination, biofilm production and nutrient imbalances that can upset the growth of the plant and also decrease the efficiency of the system. It is also important for nutrient uptake efficiency and for compliance with food safety regulations (Jafari et al., 2024).

**Spotting and Removal of Plant Debris:**

The Debris blocking the air flow, promoting microbial growth and biofilm development on system surfaces. Regular debris removal alleviates pathogen propagation and keeping water quality. Hydroponic systems can harbour pathogenic microorganisms in biofilms such as Pythium and Fusarium species associated with root rot and other plant diseases (Jafari et al., 2024), implying a potential risk to plant crops if biofilms are left unchecked.

**Cleaning Spills Immediately:**

When excess fertilizer is spilled or nutrient solution is spilled, that can also promote excess growth of the microbial community, which again leads to the growth of algal blooms and the formation of biofilms in the system. Contamination risks are minimized as much as possible with rapid clean-up with relevant disinfectants (e.g., hydrogen peroxide or peracetic acid). Research shows that spills not being cleaned in time can lead to transmission of waterborne pathogens and clogging of components in irrigation systems (Jafari et al., 2024).

**Monitoring Water Quality:**

Regularly detecting pH, electrical conductivity (EC) and dissolved oxygen (DO) are indispensable to reach a balanced nutrient solution without harmful microorganisms. Hydroponic systems are most effective operating at specific pH levels (5.5–6.5), as controlling pH is critical because it optimizes nutrient solubility whilst restricting the precipitation of minerals (Jafari et al., 2024). Monitoring electrical conductivity (EC) is used to ensure that concentrations of nutrients never exceed levels that could inflict harm on plants and can help determine if nutrient imbalances or deficiencies are present. DO levels must also be managed because a root zone deprived of oxygen will promote the development of anaerobic bacteria and thereby favour root disease. (Jafari et al., 2024) highlight the relevance of real-time water quality monitoring and filtration strategies and that preventing microbial and chemical contamination of hydroponic systems is critical for successful hydroponics and ultrafiltration and reverse osmosis are significant practices for ensuring this.

**2.2 Weekly Cleaning and Disinfection Protocols**

**Cleaning and flushing pipes**:

* Hydroponic pipes and tubing should be flushed regularly with clean water to remove microbiological and mineral deposits. According to Tham et al. (2024).
* Low concentration hydrogen peroxide (H2O₂) solution (0.1%) could prevent the formation of biofilm.

**Reservoirs and growth trays cleaning**:

* Algae and microbial films can accumulate in trays and water tanks, restricting nutrient flow and creating a breeding ground for infection.
* Clean surfaces with a diluted peracetic acid (PAA) solution and a soft brush or sponge.

**Inspect and clean air circulation unit**:

* Cleaning and dusting fans and vents to provide sufficient ventilation and reduce the quantity of fungous spores in the air.

**Instrument & apparatus sterilization**:

* Scissors, pruning shears, and measuring tools to prevent cross-contamination must be disinfected with 70 % isopropyl alcohol before and after use.

**3. Common Environmental Conditions in Hydroponics**

Hydroponic systems get rid of soilborne diseases, however bacterial, fungal and waterborne illnesses can impact on them. Hydroponic systems share a nutrient individual solution and with high humidity many diseases can easily spread. Here are the most common hydroponic plant diseases (and their causes) that exist, along with management tips.

**3.1 Root Rot (Pythium spp.)**

Root rot, caused by Pythium fungi that thrive in stagnant, low-oxygen water, is one of the most devastating diseases in hydroponic agriculture.

**Symptoms:**

The roots turn from shiny, white to mushy, slimy, brown. Plants droop and grow partially stunted, even with enough nutrients. Decomposing plant waste makes the root zones stink.

**Prevention and Treatment:**

* Ensure that the nutrient solution is well oxygenated with air pumps or aerators.
* Avoid excessive nutrient feeding because excess organic matter encourages microorganisms.
* Use biological controls to retard fungal growth including Bacillus subtilis and Trichoderma spp. (Dong & Feng 2022).
* Hydrogen peroxide (H2O₂): Microbial control can be provided using 0.1% H2O2 on infected roots.

**3.2  Powdery mildew (Erysiphe spp.)**

It is caused by a fungus called powdery mildew which forms white, powdery patches on the leaves and stems. It flourishes in humid environments with poor ventilation.

**Symptoms:**

Leaves and stems develop spots that look like white flour. The curling and yellowing of the leaves lead to reduced photosynthesis. Inside enclosed hydroponic systems, the fungus spreads quickly from plant to plant.

**Prevention and Treatment:**

* Improve air circulation: Use oscillating fans and ensure that plants are spaced adequately apart. With Organic Control Measures Use neem oil or fungicides containing sulphur.
* Keep humidity below 60% to inhibit the germination of fungus spores.

**3.3 Bacterial wilt (Ralstonia solanacearum)**

Bacterial wilt, a bacterial disease that is highly contagious, clogs the vascular tissues of plants, preventing them from absorbing water.

**Symptoms:**

Dark spots and tips on leaves or stems sudden wilting, which can occur even when sufficient moisture is available. Inside the stems, brown vascular striping is evident when cut. Plants start to droop and turn yellow, which leads to death.

**Prevention and Treatment:**

* Plant, disease-resistant varieties wherever possible.
* Clean hydroponic parts and trimming implements regularly.
* Remove and dispose of infected plants immediately, to prevent the bacteria from spreading.

**3.4 Botrytis (Gray Mold) (Botrytis cinerea)**

A fungus known as botrytis, or gray mold, attacks stems, leaves and flowers and coats their surfaces with a grayish moldy film.

**Symptoms:**

They also cover the development of gray, fuzzy mold on fruit surfaces, leaves, and stems. Bowen, who is based in Wisconsin, said collapsing, infected tissue withdraws water. Cool, humid conditions are favorable for the rapid spread of disease.

**Prevention and Treatment:**

* Keep humidity below 60% and improve air circulation.
* Immediately remove and destroy all infected plant parts.
* Use biological fungicides or fungicides based on copper for disease management.

**4. Microbial Contamination in Hydroponics and Biofilm Formation**

Hydroponic systems have a continual flow of nutrient rich water which creates a desirable environment for microorganisms to grow quickly. Thin plastic coating can also cause important food safety concerns when dangerous bacteria such as Salmonella, E. coli and Listeria are involved (Tham et al. 2024).

**4.1 Biofilms Involved in Formation and Their Risks**

Biofilm refers to structured communities of microorganisms that attach itself to surfaces and secrete an extracellular polymer matrix that renders them resistant to conventional cleaning agents. It has been shown that robust biofilm-forming bacteria like Pseudoxanthomas Mexicana and Corynebacterium tuberculostearic promote Salmonella colonization in hydroponic nutrient solutions (Tham et al., 2024). This indicates the critical need for effective and frequent sanitization to prevent biofilm development.

**4.2 Transmission of Pathogens**

Unlike soil-based farming, which has soil as a buffering material, hydroponic systems lack an internal microbial filtering system. Accordingly, water-borne pathogens can rapidly proliferate, and take over the nutrient solution, and infect the whole system if the nutrient solution is not properly sterilized.

**5. Methods for Cleaning and Disinfection**

Cleaning and disinfection are important to inhibit the growth of microbes in hydroponic systems and therefore maintain food safety.

**5.1 Cleaning the Hydroponic System**

Cleaning is required as algae will form, biofilm will build up, and organic debris will scatter. Among the best practices are:

* **Mechanical cleaning:** Is scrubbing surfaces and systems to inhibit biofilm growth.
* **Disinfectant flushing**: Using cleaning solutions on piping systems and water reservoirs between the crop cycles.
* **Rinse Thoroughly**: To protect plants from chemicals, ensure no traces remain of any disinfectant.

**5.2 Disinfectants that work and the way it works.**

Hydroponic systems can utilize a variety of disinfectants which reduce microbial contamination and biofilm formation. Table comparison of popular sanitization agents, efficacy, application techniques and safety issues.

Table 1: **Comparison of popular disinfectant’s**

| **Disinfectant** | **Target Organisms** | **Concentration & Exposure Time** | **Effectiveness** | **Application Method** | **Safety & Limitations** | **Reference** |
| --- | --- | --- | --- | --- | --- | --- |
| **Sodium Hypochlorite (NaOCl)** | *Salmonella, E. coli, Listeria*, Biofilms | 500 ppm for 12 hours | Highly effective | Flushing, soaking surfaces | Risk of chlorine by-products; requires rinsing | Tham et al. (2024) |
| **Hydrogen Peroxide (H₂O₂)** | Bacteria, Fungi, Viruses | 3-5% solution; requires 24-hour exposure | Moderately effective | Spray or direct application | Can degrade quickly; corrosive at high concentrations | Sela Saldinger et al. (2023) |
| **Sodium Percarbonate (SPC)** | Biofilms, *Pseudomonas* spp. | 1-2% solution for 12+ hours | Effective but slow | Surface soaking | Environmentally friendly but requires longer action | Tham et al. (2024) |
| **Peracetic Acid (PAA)** | Bacteria, Spores, Fungi | 85-150 ppm; 10-30 min contact | Highly effective against spores & fungi | Surface sanitization | Short lifespan, can cause irritation | Barnhart et al. (2015) |
| **Quaternary Ammonium Compounds (QACs)** | Gram-positive & Gram-negative bacteria | 200-400 ppm; 15 min contact | Effective against bacterial biofilms | Surface wiping, immersion | Residual toxicity, requires proper rinsing | Van Os (2008) |
| **Ozone (O₃)** | Bacteria, Viruses, Algae | 0.5-2.0 ppm in water | Rapid disinfection | Dissolved in irrigation water | Unstable; requires special equipment | Faicán-Benenaula et al. (2024) |
| **UV-C Radiation** | Bacteria, Spores, Algae | 200-280 nm wavelength | Very effective; prevents regrowth | Direct water exposure | Requires continuous monitoring and energy input | Bertrand (2020) |

In hydroponics system the effectiveness of the disinfection methods is based on same core criteria like the target microbial organisms, concentration and exposure time, impact on plants and the method’s compatibility with the infrastructure of hydroponics. A disinfectant is successful when it is broad spectrum (or when it is capable of targeting multiple organisms at once like bacteria, fungi, viruses etc) and also is safe for environment as well as application to the plants. For example, sodium hypochlorite (NaOCl) is a broad-spectrum disinfectant which is fast acting and is highly effective, but its dosage must be carefully measured as it can lead to environmental degradation by its phytotoxic effects (Baudoin et al., 2017). UV-C radiation and Ozone (O3) are some examples of physical methods of disinfection. These are highly effective against water borne pathogens and doesn’t produce any residue (Thakur et al., 2023). To conclude, combining of routine mechanical cleaning with disinfectants enhances the control of microbial growth and spread which in turn provides long-term sustainability of the hydroponic system.

**5.2.1 Hydrogen Peroxide (H₂O₂) Hydroponic Disinfectant Dosage:**

Hydrogen peroxide is frequently used in hydroponic systems as it is an oxidizing substance, meaning it can kill bacteria, fungi and viruses. The dosage is based on adequate concentration over long period to enable better efficiency against biofilm formation and spores (Lau & Mattson, 2021).

Table 2: **Recommended Dosages Of H₂O₂ and their effectiveness**

| **Application** | **Recommended Dosage** |  **Time** | **Effectiveness** |
| --- | --- | --- | --- |
| **Reservoir Disinfection** | 35% H₂O₂ at **50–100 ppm** | Continuous | Controls pathogens in nutrient solution |
| **Surface Sanitization** | 3–5% H₂O₂ solution | 15–30 minutes | Kills bacterial and fungal pathogens |
| **Seed Treatment** | 3% H₂O₂ for **5 minutes** | Rinse after treatment | Reduction in seed-borne pathogens |
| **Biofilm Removal** | 3–5% H₂O₂ with agitation | 24 hours | Breaks down biofilms |

While persistent biofilms may need higher concentrations, overuse can harm the roots and degrade essential nutrients. Flow treatment and post-rinsing are therefore essential to control dosage as much as possible (Tham et al., 2024).

**6. How Do Farmers Manage Pests and Diseases in Hydroponics?**

While hydroponics removes soil-borne disease challenges, plants grown in hydroponic systems are still vulnerable to fungal infection and airborne pests. Improper management of these threats can have significant adverse effects on crop yield, plant health, and overall system productivity. Flying intruders like aphids, whiteflies, and fungus gnats can bring plant diseases into the grow room, reproduce quickly, and attack root systems, impairing nutrient uptake (Tham et al., 2024). In contrast to conventional farming, hydroponic systems have no soil, a natural microbial buffer, leaving plants more susceptible to airborne pathogens and diseases spread via water and human handling (Tokunaga et al., 2024). However, to reduce the risks, a multifactorial pest management approach is needed to protect a safe food environment, sustainability of the ecosystem, and compliance with agricultural regulations (e.g., Good Agricultural Practices (GAP) and Food Safety Modernization Act (FSMA), Northeast Center to Advance Food Safety (NECAFS), 2024). This section will describe some of the most common pests you will encounter in your hydroponic system, and it will also cover best management practices related to pest control, such as Integrated Pest Management (IPM), biological control methods, physical barriers and the use of safe environmental chemicals.

**6.1 Common Hydroponic System Pests**

The growth and yield of the plant are affected by insect pests which also serve as the vectors for some of the plant pathogens and diseases in hydroponics. Such pests are generally well established in controlled environments with humidity and temperature favourable for their fast reproduction and infestation (Bertrand, 2020). Some of the most common hydroponic pests are as follows:

* **Aphids (Myzus persicae):** Tiny sap-sucking bugs that suck nutrients from plants leading to weak stems and deformed leaves, less efficiently photosynthesize. Aphids are rapid reproducers and they create large colonies that stunt the growth of plants and make them more susceptible to viral infections (Dong & Feng, 2022).
* **Whiteflies (Bemisia tabaci):** Whiteflies are known carriers of plant viruses, including Tomato Yellow Leaf Curl Virus (TYLCV) and Cucumber Mosaic Virus (CMV). They produce honeydew, promoting sooty mold diseases that reduce the photosynthetic activity of the host (Jafari et al., 2024).
* **Fungus gnats (Bradysia spp):** They deposit eggs in nutrient solutions, and their larvae damage root systems by feeding on root hairs and transmitting microbial diseases like Pythium root rot (Faicán-Benenaula et al., 2024). They can seriously interfere with water and nutrient absorption, inducing wilting, and even death, of the plant.

In contrast to soil-based farming, where natural predators and microbial competition keep pest populations in check, hydroponic systems require strategic intervention to prevent infestations. If not controlled, these pests can proliferate quickly in the recirculating water system and affect the whole crop (Tham et al., 2024). As a result, hydroponic farmers have to put in place proactive pest management methods to keep the plants healthy and the system running effectively.

6.2 Integrated Pest Management (IPM) for Hydroponic Farming

Integrated Pest Management (IPM) is a pest control regimen that integrates a series of pest control methods that diminish pest population with minimum use of chemical pesticide (Sela Saldinger etal., 2023). This combines biological, physical and chemical control methods to create a sustainable pest management system within hydroponics farms. By decreasing dependence on synthetic pesticides, the potential environmental impact of pesticides is also reduced, maintaining food safety and easing regulatory actions (Jafari et al., 2024).

Cultural and technological practices also play an important role in implementing effective IPM strategies in hydroponics system. For example, cultural practices like crop rotation, sanitation and selection of resistant crop variety can help in pest control by breaking or interrupting the pest life cycle thereby stopping their population growth. Cleaning the tools, disinfecting the work station and the management of plant residue are all the part of good agriculture practices (GAPs). These practices reduce pest introduction and breeding in the greenhouse environment. Such practices are crucial in hydroponics where the pest can spread rapidly (Baudoin et al., 2017).

To enhance pest control method, the incorporation of monitoring system is important. For example, the hydroponics system can be integrated with the environmental sensor which provides data on the temperature and humidity levels which can be used to inhibit pest development (Savvas & Gruda, 2018). IPM planning enhances overall crop protection using sodium hypochlorite against many plant pathogens which are often the cause for pest related diseases transmission (Copes & Ojiambo, 2021). The most critical and underemphasized area of IPM is the education and training of farmers. According to (Baudoin et al., 2013; Baudoin et al., 2017), the keys to sustainable pest management and its success in hydroponics and greenhouse systems is early detection, farmer awareness and pest monitoring.

6.2.1 Biological Control

Biological control is a method of controlling pests based on the use of their natural enemies, including predators, parasites or pathogens. Common species used for aphid suppression in hydroponics are ladybugs (Hippodamia convergens) and lacewings (Chrysoperla carnea) (Dong & Feng, 2022). The predatory mite (Amblyseius swirskii) similarly doesn't translocate any viruses between plants, with the predation of thrips and whiteflies effectively halting the spread of plant viruses (Jafari et al., 2024). Biological control is an essential component for sustainable agriculture that can decrease pesticide application and keep ecological balance in the growing environment (Tokunaga et al., 2024).

6.2.2 Physical Barriers and Environmental Controls

In hydroponic farming, physical pest control techniques are one of the most important tools because they offer a non-chemical way to manage infestations. Air filtering systems and insect netting help to keep airborne pests out of the space in which crops are grown, thus lowering the risks of infestation (Tokunaga et al., 2024). Sticky traps, especially yellow traps, have emerged as an effective tool for trapping and monitoring whiteflies, aphids, and fungus gnats (Tokunaga et al., 2024). (Faicán-Benenaula et al., 2024) point out that by putting yellow sticky traps at the plant canopy level we can effectively decrease the populations of adult pests, interrupting their reproductive cycles and preventing outbreaks on a larger scale. Traps should be installed at 1–2 m² per trap, depending on pest severity (Faicán-Benenaula et al., 2024).

**7. Food safety regulation**

Food safety is a core element of Good agricultural Practices (GAP) in hydroponic farming and abiding by the rules is important to minimise contamination risks throughout the production cycle. The (Baudoin et al., 2013) stresses on the priority of water quality, hygiene and traceability systems so that the consumer health in greenhouse vegetable production can be safeguarded. Operators are advised to implement hazard analysis and critical control point (HACCP) strategies that will cover all possible risks related to biological, chemical and physical hazards from seed to harvest. Also, primary requirements including regular health check-ups of farm workers, strict sanitation routines and disinfection of equipment should be followed. The (Baudoin et al., 2017) further provides an in-depth approach by recommending the implementation of record-keeping and routine risk assessments to ensure compliance with the national and food safety regulations. In addition to this, attention to certified seeds, potable water and pathogen -free media serves as an important aspect of hydroponic farming in Southeast European countries. As a whole, these guidelines are important for promoting high-quality produce and instilling confidence in hydroponically grown vegetables.

**8. Conclusion**

This paper is very important to the scientific community since it discusses significant aspects of hydroponic system cleanliness, which is necessary to guarantee safe and sustainable food production. Through the assessment of different disinfection techniques and integrated pest management plans, the evaluation offers important information about preserving biosecurity while reducing the environmental impact. Even though sodium hypochlorite is still the best disinfectant, alternative environment friendly disinfectants are being discussed, which supports further attempts to create sustainable farming methods. The focus on future research avenues also promotes innovation in disinfection and microbiome management technology, which eventually improves the resilience and efficiency of controlled-environment agriculture. IPM techniques offer sustainable pest management through decreased dependence on pesticides.

**9. Future Research Directions**

* **Exploring New Hygiene Products**: Ozone therapy and UV-C irradiation are being explored as chemical-free alternatives.
* **Microbiome Control**: Understanding how beneficial microbes aid in hydroponic sanitation.
* **Intelligent Surveillance Systems**: AI-powered sensors that monitor for pathogens in real-time. Science-based best practices drive productivity, safety and sustainability in future hydroponic farming (Dong & Feng 2022).

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