



# Pest Management in Hydroponics Crop Production: Challenges and Solutions

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## Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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## ABSTRACT

Soilless cultivation, specifically hydroponic structures, is gaining attraction as a sustainable and green opportunity to conventional soil based agriculture. Hydroponic cultivation requires precise parameters adjustments inclusive of temperature, pH, water and nutrient formulations for optimized plant health and productivity. However, these system have numerous challenges like pest and pathogen attack and further management, nutrient recycling and environmental impact. Therefore, present review discusses the comparative advantages and obstacles of open and closed hydroponic systems, highlighting the susceptibility of closed systems to pathogen spread and vehicle toxicity due to root exudates. The significance of IPM, plant health monitoring and the use of mycorrhizae in greenhouse hydroponic is emphasized in current study. Various strategies for managing the pathogens and toxic compounds in nutrient solutions are evaluated, which include activated carbon adsorption, electro-degradation, semiconductor photo-catalysis, ultraviolet irradiation, hydrogen peroxide treatment and filtration strategies. The article underscores the need

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for effective, sustainable and scalable treatment procedures tailored to closed hydroponic systems to make sure high productivity even as minimizing the environmental dangers. Moreover, it identifies the opportunities for scientific studies into optimizing the microbial health in substrates and enhancing the overall IPM implementation under controlled environments for sustainable crop production.

**Keywords:** Hydroponics; pest control; agriculture; environment; crop production; sustainability.

## 1. INTRODUCTION

In agriculture, soil is often the most accessible support medium offering vital nutrients water and micro and macro fauna and flora (Khan, 2018). However, urbanization environmental degradation and climate change are some of the reasons that are reducing the amount of fertile soil surface and sufficient water supply available for agriculture worldwide (Chen, 2007). Agricultural practices are more difficult by the presence of disease causing pests and pathogens (Sambo *et al.*, 2019). Climate change is predicted to make this matter even more worst by expanding the ranges of species and possibly altering plant pathogen interactions (Singh *et al.*, 2023). Inappropriate farming practices, inadequate drainage and the intensification of production cycles with monocultures becoming more prevalent and have led to pathogen spread soil compaction and degradation and other related problems (Khan, 2018). Hydroponic farming which involves placing plant roots directly in contact with nutrient solutions rather than soil is thought to be a highly effective method for maximizing yields per unit area and producing high quality crops in the shortest amount of time (Mahjoor *et al.*, 2016). This approach not only reduces the amount of land used for plant production, but also, minimizes the environmental impact of plant production by optimizing the nutrient utilization in the hydroponic solution. In a hydroponics system the nutrients solution are essential to a successful crop (Valentinuzzi *et al.*, 2015). The physiological development and function of the plant roots are influenced by the nutrient levels in the hydroponic solution as well as the interactions between various nutrients (Sambo *et al.*, 2019). There are two primary types of hydroponic systems *viz.* open and closed systems. The nutrient solution only passes through the system once in an open system before being disposed of (Nederhoff & Stanghellini, 2010). Although this might result in a straight forward and manageable system as the constant flow of water and nutrients causes significant waste. The control of disease and management of changes

in nutrient ion concentration in the nutrient solution are the two elements of a closed hydroponics system that often receive the most attention (Ehret *et al.*, 2001). Plant roots also release exudates containing substantial quantities of organic acids and phenolic compounds. This novel concept holds great promise for addressing the broad range of biotechnological and environmental challenges with the potential to enhance the bio-energy and bio-resource recovery as well as organic waste treatment and real time water quality monitoring using biosensors (Hoang *et al.*, 2022).

Soilless farming method needs a constant supply of water and nutrient solution either openly or in closed circulation unlike soil-based plant culture. Open systems are easy to set up technically and root infecting viruses don't travel very far. Too much nutritional solution leaks out endangers the ecosystem. Although it requires precise crop management recirculating fertilizer solution provides ecological advantages. Pathogens have the ability to spread and threaten the entire crop under specific situations. However, only closed systems should be taken into consideration nowadays (Sevda *et al.*, 2020). Numerous technologies are available that have varying risks of causing root system damage to plants owing to different diseases. There is a wide variety of substrates available for soilless culture they must always be pathogen free when first applied. They need to be cleaned before being used again. *Phyto-pathogenic* fungi like *Pythium*, *Phytophthora* and *Olpidium* are the most harmful followed by bacteria, viruses, and nematodes. To prevent issues from the beginning, the gardener should be careful to only transfer healthy seedlings. In addition, to providing surface water for irrigation greenhouse buildings can act as sources of infection. In order to minimize stress on plants soilless cultivation methods offer the significant benefits of optimizing growth parameters such as temperature water, pH and nutrients. Large mono-crop enterprises may decide to sterilize their irrigation water. Many useful choices are available including membrane slow or bio-

filtration heating and different chemicals ozone, hydrogen peroxide, chlorine and iodine. In addition to fluorescent *Pseudomonades* biological treatment of root infesting pathogens provides some extremely intriguing novel strategies, such as using strains of *Bacillus*, *Streptomyces*, *Trichoderma*, non-pathogenic *Fusarium*. New avenues for research must be explored in order to optimize the growth circumstances of beneficial microorganisms that are either spontaneous or selectively exploited in the substrate.

### 1.1 IPM Concept and Implementation

IPM still lacks a single, widely accepted definition. Although there are many different and plausible interpretations of what IPM is, it basically refers to knowing the principles and available solutions for crop protection and eventually decision-making. Good agricultural practices monitoring and diagnostic systems, phyto-sanitary measures and the minimal amount of natural enemy control are all included in IPM quantity of insecticides high grade and when needed. IPM is therefore a crucial component physical and cultural control methods. Scouting and monitoring are used to identify the first signs of illness and pests, followed by the extent of infestation. Recording pests and diseases in order to document and monitor changes in pest and disease concentrations, the crop's infested region, and the precise location of individual plants. Keeping track of information on pests and diseases, crop seasonality, climate and weather forecasting and nearby cropping initiatives. Establishing economic benchmarks help to ensure that the control technique should be applied at the appropriate time. Estimating and forecasting the social, ecological and economic effects. Choosing, combining, and putting into practice biological, physical and cultural control methods solutions tailored to a particular pest or disease with the least hazardous formulation and where appropriate use an alternative chemical group.

### 1.2 Health and Management of Plant

Seven characteristics of plant health must be taken into account for all berry species to attain their maximum economic potential. A situation where changes are always needed but don't addresses the root cause might result from a compromise in one or more of the sectors. Berries need to be regularly surveyed for the presence of pests and diseases, followed by pressure. Sticky trap, biased, and random

inspections are used to accomplish this. An unbalanced examination focuses on clear, visible signs of pest infestation and poor plant health, such as insect damage, wilting and yellowing (Sevda et al., 2020). During a random investigation a path through the berry crop and making sporadic stops at routine checkpoints to identify pests or illnesses before they manifest themselves assessment of the level of infestation and ultimately, an indication of the level of control needed after a control strategy has been adopted and applied. Sticky traps are color specific yellow or blue pieces of flat card covered with a waterproof adhesive. They are generally rectangular in shape and measure roughly 15x25cm.

### 1.3 Mycorrhizae under Greenhouse Hydroponic Berry Production Systems

A symbiotic relationship between the fungus and plant roots is formed by *mycorrhizae*. Asexual organisms known as *arbuscular mycorrhizal* fungus produce spores and *arbuscles* by penetrating plant roots with their hyphae. They protect host plants from biotic and abiotic stressors and aid in the absorption of nutrients particularly N, P and Zn. *Arbuscular mycorrhizal* fungus has been widely utilized in conventional soil-based strawberry and raspberry cultivation, but substrate or hydroponic production of these fruits has just lately become popular. For instance, a strawberry trial at East malling research was unaffected by a discernible decrease in *arbuscular mycorrhizal* fungus plant root colonization in substrate as opposed to soils because commercial fertigation regimes increased Class 1 fruit by an average of 10-20% and reduced water use by 40% (Robinson Boyer, 2016).

## 2. CHALLENGES ASSOCIATED WITH CLOSED HYDROPONIC SYSTEMS

### 2.1 Autotoxicity

In closed hydroponic systems, auto toxicity, a type of allelopathy in plants, might be problematic. Auto-toxicity typically happens when substances in naturally occurring root exudates build up over acceptable thresholds as the nutrient solution is recycled. Several plant phenotypic indicators, such as shoot and root development, flower count, harvested fruit per plant, and total yield, are used to quantify the loss of plant production (Miller, 1996). Since roots are the first site of interaction with

autotoxins in the *rhizosphere*, *autotoxicity* in plants impairs their ability to absorb ions and nutrients (Asaduzzaman & Asao, 2020). Depending on variables including plant type and the differential in concentration between the roots and the soil, the rate at which organic molecules are lost from plant roots varies. More than 200 chemical molecules, including a variety of organic acids like *adipic*, *maleic*, *succinic*, *palmitic*, *vanillic*, *lactic*, *benzoic* and *salicylic* are found in plant root exudates. Benzoic acid, in example, has been found in repurposed plant nutrient solutions and is known to be a strong inhibitor of germination and growth (Kitazawa *et al.*, 2005; Mondal *et al.*, 2015). Plant performance during cultivation in closed hydroponic systems (Hosseinzadeh *et al.*, 2017), as well as the negative effects of root exudates and auto toxicity on plants, including lettuce, tomato, strawberry, cucumber, and beans (Kitazawa *et al.*, 2005; Asaduzzaman & Asao, 2012; Salam *et al.*, 2024). In strawberries grown in closed hydroponics, yield decrease owing to unidentified variables has been documented. The buildup of aromatic compounds in the nutrient solution showed growth inhibiting effect in tomato hydroponics. According to Asaduzzaman & Asao (2012), root exudates more especially phenolic acids that accumulated in the nutrient solution were the cause of the strawberry plants' slower growth in hydroponic systems. Hydroponic cultures of rose seedlings both root and shoot growth were observed to diminish due to root exudates (Sato, 2004). That root exudates caused a decrease in cucumber fruit yield during the late reproductive stage, with 2, 4-dichlorobenzoic acid identified as the most effective inhibitor. Both biotic (Hickman *et al.*, 2021) and abiotic (Inderjit & Weston, 2003) plant stress situations frequently result in an increase in the synthesis and exudation of allelochemicals as well as an overall increase in the production of root exudates. The recognition and reaction of plants to root exudates from other species has also been demonstrated (Semchenko *et al.*, 2014; Rai *et al.*, 2024). Smaller facilities that cultivate several species together may be affected, even if this is not a problem for large commercial operations that usually grow a monocarp. It is unlikely that plants in a well-managed hydroponics system will encounter abiotic stressors.

## 2.2 Pathogen Development

In addition to providing the best growing conditions for plants, hydroponic systems can

also serve as a breeding ground for plant diseases. If a pathogen is introduced into a hydroponics system, it can affect quality and production and cause significant crop loss if left untreated (Stanghellini & Rasmussen, 1994). Both open and closed hydroponic systems can harbor harmful bacteria, but if proper measures are not taken to keep them from reentering the system, their effects are exacerbated when the nutrient solution is recycled. A hydroponics system's crops are usually kept in controlled environment structures that range in complexity from glass houses to high tunnels to fully enclosed plant factories that rely only on electric light. Numerous molds and mildews, such as powdery mildew and grey mold, as well as a variety of insect pests can cause problems in a regulated plant growing environment. Some infections such *Pythium*, *Phytophthora*, *Fusarium* and *Verticillium* species and some plant viruses, can easily travel in the nutrient solution and spread to new host plants, whereas other pathogens spread across a facility by airborne spores or insect vectors (Ehret *et al.*, 2001). Although it is not a plant pathogen, algae can also cause problems in hydroponic systems. They will multiply in a closed system and affect water quality parameters like dissolved oxygen, pH, and nutrient composition (Abdel-Raouf *et al.*, 2012). The algae will use up nutrients meant for the plants and may produce toxic substances that prevent plant growth (Schwarz & Gross, 2004). Schwarz and Gross discovered that algae had negative effects on lettuce grown in hydroponic systems, resulting in a significant decrease in fresh weight, shoot/root ratio, water and nitrogen uptake and others.

## 2.3 Environmental Implications

To enhance crop productivity, hydroponic agriculture techniques need a lot of water and nutrients (Gagnon *et al.*, 2010). Plant species, development phases, and weather conditions all affect how much water is released from open hydroponic systems. When compared to open systems, closed hydroponic systems use the fertilizer solution more effectively by recycling nutrients, saving about 30% of the water. In closed systems, hydroponic fertilizer solutions must be changed on a regular basis. According to (Schwarz & Gross, 2004), these solutions contain important elements such as nitrogen, phosphorous, potassium, magnesium, calcium, iron, copper, zinc, sulfur, manganese and boron. With exceeding the discharge limit by up to 994 times and surpassing the discharge norm by up

to 6-19 times, these levels are higher than the municipal and environmental discharge standards for rivers (Park *et al.*, 2021). The quality of drinking water drawn from affected surface or ground water sources may potentially be adversely affected by nitrate leaching. Other nutrients are also released by hydroponic systems but it is difficult to keep an eye on them due to a lack of knowledge about their concentrations.

#### 2.4 Activated Carbon Treatment

Due to its aforementioned qualities and low cost, activated carbon has been used extensively in the removal of many organic compounds. It is also thought to be the most popular technology for removing root exudates from closed-loop hydroponic nutrient solutions in a variety of crops such as bean, cucumber, leafy vegetables, lettuce, strawberry, taro, tomato, etc. AC adsorption is an amorphous carbon that is reasonably priced and a good performance adsorbent. The addition of AC to tomato hydroponic solution reduced the concentration of organic compounds in the solution and increased the dry weight of plants and fruit yields. Asaduzzaman & Asao (2012) demonstrated that the number of pods, fresh pod weight, seed number, and fresh seed weight of plants grown in AC free non-renewed culture medium were reduced by about half compared to those grown with AC. Biologically activated carbon utilizes granular activated carbon to remove organic matter and has many advantages, including low operational cost. Furthermore, activated carbon has a limited removal capability that decreases with time, even while it may efficiently remove phyto-toxic chemicals that have accumulated in nutrient solutions over a comparatively short period of time. Moreover, hydroponic solutions lose nutrients as well as organic pollutants due to the non-selective nature of AC treatment. Specifically, it is widely known that AC treatment can remove phosphates and nitrates (Almanassra *et al.*, 2021; Ahmed *et al.*, 2023). When nutrient retention is required in closed hydroponic systems, this type of treatment may not be appropriate, but it might be appropriate for open hydroponic systems.

#### 2.5 Electro-Degradation Treatment

For detoxifying allelochemicals in closed hydroponic systems is electro-degradation. It has been discovered that the ED process at the anode to CO<sub>2</sub> can break down phenolic chemicals from organic waste or contaminants,

such as phenol, catechol, droquinone, or benzene. Therefore, by degrading allelochemicals that leak from plants into nutritional solution, such as benzoic acid, ED may help reduce auto-toxicity. Using a ferrite rod as the anode and a titanium plate as the cathode discovered that the administration of considerably decreased the suppression of seedling growth in nutrient solutions containing benzoic acid or in nutrient solutions used for strawberry culture. Additionally, it has been demonstrated that using alternating current during the ED process accelerates the breakdown of benzoic acid and enhances strawberry quality yield and growth (Talukder *et al.*, 2019).

#### 2.6 Semiconductor Treatment

#### Photocatalytic

Because of its benefits for removing phytotoxic substances, semiconductor photo catalysis has become more and more popular. TiO<sub>2</sub> is the most widely used semiconductor because of its many benefits, including its broad spectrum of sterilization feature, complete decomposition, long repeated use, non-toxicity and lack of secondary pollution (Hosseinzadeh *et al.*, 2017a). Other semiconductors include metal oxides and sulfides TiO<sub>2</sub>, ZnO, Fe<sub>2</sub>SO<sub>3</sub>, WO<sub>3</sub> and ZnS. When TiO<sub>2</sub> absorbs ultraviolet light with a wavelength shorter than its band gap (about 385 nm), organic matter adsorbed on its surface is oxidized and broken down into CO<sub>2</sub> and H<sub>2</sub>O. This process is known as TiO<sub>2</sub> photo catalysis. According to Miyama *et al.* the germination rate was 0% prior to irradiation, indicating the potent inhibitory impact of rice husk extract. However, following 4 days of irradiation, the germination rate increased back to 100% (Miyama *et al.*, 2009). Asparagus grew better in photocatalytically treated systems than in untreated ones, according to (Sunada *et al.*, 2008). Miyama also discovered similar outcomes with roses (Miyama *et al.*, 2013).

#### 2.7 Pathogen Treatment- Ultraviolet Radiation

In hydroponic nutrient solutions, ultraviolet radiation has been shown to be an economical method of controlling infections. The hydroponic feeding solution is typically exposed to light with germicidal wavelengths between 225 and 312 nm as part of the UV treatment (Sholtes *et al.*, 2016). These systems' bulbs are often categorized as medium-pressure or low-pressure. Medium-pressure lamps emit several

wavelengths within the germicidal range, but low-pressure lamps only produce light at a single wavelength of about 254 nm. Compared to medium-pressure lamps, low-pressure lamp applications are more often documented in the literature. The main indicator of UV disinfection capacity is radiation dosage, or the energy received per unit area over a specific time period (Mamane *et al.*, 2010). According to the intensity, duration of exposure, light reflection, and refraction all have an impact on the dose and influence how much the microorganisms in the water are inactivated. The main method of eliminating pathogens is DNA damage, which results in mRNA damage and failure to replicate (Xu *et al.*, 2018). Bacteria are often the most vulnerable to this damage, followed by protozoa, viruses, and bacterial spores. UV sensitivity differs greatly between species and even between strains of the same species, and this order of sensitivity is a trend rather than a rule. UV sensitivity varies greatly between species and even between strains of the same species, therefore this order of sensitivity is more of a trend than a rule. The results may be impacted by the pathogen's origin, the lab environment, the UV equipment being utilized, demonstrated that administering UV radiation (171.6 mJ/cm<sup>2</sup>) to a circulating hydroponic system for 3 h per day reduced bacterial counts from 400 × 10<sup>3</sup> cells m/L to 50 × 10<sup>3</sup> cells m/L. (Mamane *et al.*, 2010) reported that bacterial levels were reduced from 1500 bacteria m/L to 750 bacteria m/L when recirculating water was passed by a low-pressure UV disinfection unit (2-4 mJ/cm<sup>2</sup>). Research demonstrates that continuous UV radiation can more dramatically diminish possibly disease-causing germs. Continuous UV treatment has also been demonstrated to eradicate 96.4-99.7% of bacteria at a level of 250 mJ/cm<sup>2</sup> and suppress the growth of *Phytophthora fruitum* in rockwool hydroponic systems.

### 3. DISADVANTAGES OF UV TREATMENT

The disadvantages of UV treatment include relatively high energy consumption, removal of chelated iron from the nutrient solution, device fragility and short lifespan, use of mercury (in recent years LED technology is fast growing) with associated post-use disposal issues, and high heat output requiring extensive cooling facilities (Wang et al. 2024).

#### 3.1 Hydrogen Peroxide Treatment

Hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) is an inexpensive, strong and unstable oxidizing agent that reacts to

from H<sub>2</sub>O and an O<sup>-</sup> radical. H<sub>2</sub>O<sub>2</sub> an endogenous reactive oxygen species and at low concentrations it serves as an importance signaling molecule in various plant functions that can positively impact plant growth and yield (Hosseinzadeh *et al.*, 2017; Shubham *et al.*, 2023; Zheng *et al.*, 2020). H<sub>2</sub>O<sub>2</sub> oxidizes the pathogens and plant exudates in a manner similar to that of ozone treatment. The by-products produced by the decomposition of H<sub>2</sub>O<sub>2</sub> are H<sub>2</sub>O and O<sub>2</sub>. In hydroponic nutrient solutions, the released (unreacted) oxygen from the H<sub>2</sub>O<sub>2</sub> breakdown can boost dissolved oxygen content in the root zone and assist decrease oxygen loss that may occur owing to biofilm and microbial respiration. recommends varying H<sub>2</sub>O<sub>2</sub> dosages for various diseases, including viruses (0.05%), *Fusarium spp.* (0.01%) and *Pythium spp.* (0.005%). However, plant roots are also harmed at a concentration of 0.05%. Although this treatment approach is low-cost and has the potential to be a useful tool for managing microbial growth in hydroponic systems, caution must be used to maintain dosage amounts and avoid overdosing.

#### 3.2 Filtration

Filtration can take the form of either high tech or low-tech solutions to remove pathogens from nutrient solution. The system's total surface area may need to be very big to offer the required filtering capacity for a greenhouse facility due to the sluggish rate at which the liquid percolates through the filter. It might be essential to prevent the filter from freezing in colder climates, which would need more capital expenditure. In the future, these systems may be smaller thanks to the development of quick sand filtering systems (Jeon *et al.*, 2019). Although fungal pathogens can be successfully eliminated from the nutritional solution using a sterile filter bed, the elimination of smaller organisms seems to rely on microbial colonization. Although fungal pathogens can be successfully eliminated from the nutritional solution using a sterile filter bed, the elimination of smaller organisms seems to rely on microbial colonization. It's unclear how well slow sand filtration works to get rid of harmful plant viruses from nutrient solutions, although it has been shown to get rid of tobacco mosaic virus from irrigation runoff (Oki *et al.*, 2017). Viral elimination did not happen until 6-8 weeks after viral exposure, and this removal was dependent on the filter's microbial colonization. Pathogens can also be successfully eliminated from a nutritional solution by membrane filtration;

however, in practice, these systems may be troublesome in a greenhouse setting due to their propensity for clogging and leakage. It is unclear how well slow sand filtration works to get rid of harmful plant viruses from nutrient solutions, although it has been shown to get rid of tobacco mosaic virus from irrigation runoff (Oki et al., 2017; Shivani et al., 2024). Viral elimination did not happen until 6-8 weeks after viral exposure, and this removal was dependent on the filter's microbial colonization (Oki et al., 2017). Single and double membrane filter systems did not offer reliable crop disease protection over an extended period of time, according to Schuerger & Hammer, (2009).

### 3.3 Beneficial Microbial Activity in Hydroponics

*Pseudomonas spp. aeruginosa, aureofaciens, chlorophyll roraphis, corrugate, fluorescens, fulva, marginalis, etc. Bacillus spp. Enterobacter spp. (aerogenes), Streptomyces spp. Gliocladium spp. catenulatum and Trichoderma spp.* Among the plant growth-promoting rhizobacteria that are present in hydroponic systems and have a positive impact on crop quality and quantity. The makeup of the microflora in hydroponic systems is often influenced by environmental condition temperature, pH, humidity and nutrition supplies. Additionally, in hydroponic tomatoes and cucumbers, root infections brought on by Pythium or Fusarium can be effectively reduced by bio control agents produced by *Glio cadium catenulatum* (Khalil & Alsanius, 2010).

### 3.4 Application of Bio-Electrochemical Systems in Hydroponics

The ability to combine the biodegradation of organic wastes with the generation of electricity or other value-added products makes it possible to develop new technologies for hydroponic nutrient solution treatment using bio-electrochemical systems such as Microbial full cell and Microbial electrolysis cell's (Pant et al., 2010). Bio-electro chemical system have the potential to take the place of current therapy approaches. Because of the strong electro-active microbial community's capacity to efficiently eliminate the majority of bio-refractory pollutants, Bio-electro chemical system has already drawn a lot of interest from researchers (Bajracharya et al., 2016). Research is now under progress to employ this innovative method to improve the performance of hydroponic systems because of

the great adaptability of bio-electro chemical system. The subsequent sections outline established Bio-electro chemical system uses in hydroponic plant culture and offer prospective bio-electro chemical system uses for the reuse and treatment of nutrient solutions.

### 3.5 Future Opportunities

Despite the advantages indicated above, hydroponic systems have drawbacks since, in closed systems, the feed solution is constantly recycled and utilized again. Such recycling creates vulnerabilities, including the buildup of root exudates and the possibility for rapid illness and dangerous organism growth. While some of these vulnerabilities may be addressed, others call for more investigation. Hydroponic nutrient solution is traditionally managed via physical activated carbon for example chemical ultra-violate rays ozone, H<sub>2</sub>O<sub>2</sub> and biological treatment techniques. The quality of hydroponic water released into the environment and the enhancement of fertilizer solution reuse are, however, hampered by issues like high treatment costs, excessive energy consumption chemical residues. Bio-electrochemical systems microbial full cell and microbial electrolysis cell provide a novel solution with a number of clear advantages, despite their inability to solve all of these issues. Hydroponic water released into delicate receiving streams is effectively treated. Preventing the accumulation of root exudates in closed systems dual use as biosensors for plant monitoring and hydroponic water treatment system. The exceptional capacity to simultaneously break down organic materials and generate chemicals or power resulting in energy savings

## 4. CONCLUSION

Hydroponic and soilless farming methods offer great potential for sustainable agriculture, particularly in areas with restricted arable land and water resources. But the complexity of dealing with closed structures requires a deep knowledge of plant physiology, pathogen dynamics and nutrient interactions. This assessment emphasizes the want for incorporated control practices which include IPM, biological controls and water sanitation strategies to ensure most useful crop overall performance and gadget durability. Even as modern treatments like UV irradiation, activated carbon and photo-catalysis present powerful tools for dealing with phyto-toxicity and disease, every

method comes with operational trade-offs. Environmental issues, especially the nutrient runoff and chemical accumulation ought to additionally be addressed through higher tracking and waste management protocols. Studies need to prioritize optimizing microbial communities and refining non-chemical interventions to make soilless agriculture greater resilient and commercially feasible.

## DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT etc) and text-to-image generators have been used during writing or editing of this manuscript.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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