Nanobotanica
1(1): 2026

Review Article

NANO-ENABLED HYDROPONICS: THE INTERSECTION OF PRECISION AGRICULTURE AND NANOBIOTECHNOLOGY

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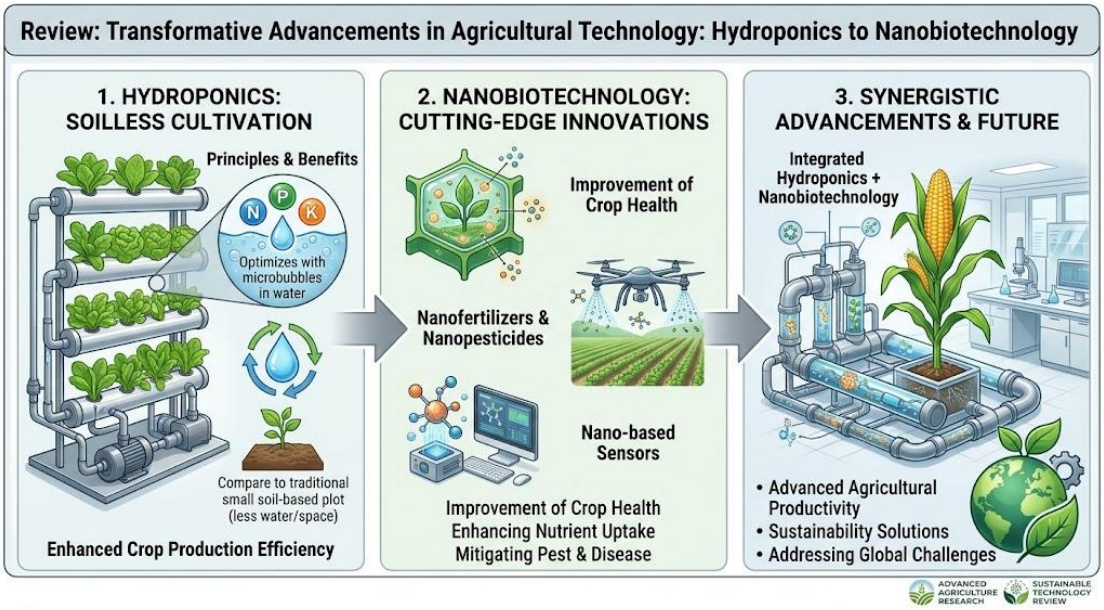
ABSTRACT

This review explores transformative advancements in agricultural technology, focusing on the evolution from hydroponics to nanobiotechnology. Hydroponics, a soilless cultivation method, has significantly enhanced crop production efficiency by optimizing nutrient delivery and water usage. This review delves into the principles of hydroponics, its applications, and its benefits compared to traditional soil-based agriculture. The discussion then transitions to nanobiotechnology, which represents a cutting-edge intersection of nanotechnology and biotechnology. Nanobiotechnology offers novel solutions for improving crop health, enhancing nutrient uptake, and mitigating pest and disease impacts. The review highlights the latest research and innovations in nanobiotechnology, including the development of nanofertilizers, nanopesticides, and nano-based sensors. By examining these advanced technologies, the article aims to provide a comprehensive understanding of how they collectively contribute to sustainable agriculture and address current challenges. The integration of hydroponics and nanobiotechnology exemplifies the potential for synergistic approaches in advancing agricultural productivity and sustainability.

Keywords: Agriculture, climate, hydroponics, plants, stress.

GRAPHICAL ABSTRACT:



Received: 04-04-2026, **Accepted**: 20-07-2026, **Published**: 15-08-2026
Citation: Shahid T, Javed F, Anmol A, Afzal S (2026). Nano-enabled hydroponics: The intersection of precision agriculture and nanobiotechnology. Nanobotanica, 1(1), 36-48.
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1: INTRODUCTION

The word "agriculture" applies to the broad range of practices employed on domesticated animals and crop plants to provide food and other necessities for the world's population (Harris and Fuller, 2013). It holds immense significance in human life, providing a reliable food source and playing a foundational role in the advancement of civilization and economic activities (Bhargava *et al*., 2019). Among the various agricultural practices, conventional agriculture stands out as one of the most widely used methods. Historically defined as the cultivation of crops in soil, under natural conditions, with irrigation, and the active application of nutrients, conventional agricultural (Geoponic) practices have the potential to yield negative impacts on the environment (AlShrouf, 2017).

A technique for growing plants with no soil is called hydroponics, where plant roots obtain essential nutrients from a nutrient solution, typically enriched water. Compared to traditional soil farming, hydroponics offers advantages in nutrient and water efficiency, as well as in plant pest and disease management (Gonnella and Renna, 2021).

Aim of present study is to highlight the importance of hydroponics in this era when food security and climate change are one of the most important issues worldwide.

2: IMPACT OF CONVENTIONAL AGRICULTURE

a) Environmental degradation

Agriculture is recognized for its significant environmental footprint, primarily attributed to the chemicals synthesized in pesticides, fertilizers, growth stimulants, and other related products. Pollution sources containing pesticides are pervasive across all three environmental domains (water, air, and soil) ultimately impacting the entire food chain. Surface water, along with groundwater, can serve as conducive forms of pollution, with pesticides swiftly reaching them, particularly during rainfall events (Girip *et al*., 2020).

b) Loss of Biodiversity

The quantity, variety, and variability of living things in a particular habitat are all included in the concept of biodiversity. This includes diversity across different environments, within species, and across species (Chivian and Bernstein, 2008). The destruction of habitats has been the most major ecological effect of agricultural development on biodiversity. This, along with soil of erosion and the heavy use of agricultural chemicals like fertilizers and pesticides, poses a serious danger to biodiversity (Butler *et al*., 2007; Cozem *et al.,* 2024). Agriculture has been a major contributor to the endangerment of biodiversity, second only to urbanization (Czech *et al*., 2000; Hald *et al.,* 2023).

Conventional agriculture has been pinpointed as a primary catalyst for biodiversity depletion. The adoption of intensive farming methods, characterized by the widespread use of synthetic pesticides and fertilizers, habitat destruction, and shortened crop rotations, has caused a decline in agrestal plant communities (Kleijn *et al*., 2023). Consequently, these practices exert adverse effects on vegetation and seed banks, resulting in the reduction of arthropod, bird, and mammal species populations (Reyes *et al*., 2022; Boakes *et al*., 2024).

c) Greenhouse Gas Emissions

By energy, mostly from natural gas and oil, agricultural operations add to CO_2 emissions. This happens both in a direct way, in field work and mechanical operations and indirect way, in the pesticide and fertilizer manufacture and transportation. Changes in the ecology of soil can also result in the atmospheric release of carbon. CO_2 emissions are made worse by deforestation, as forested areas are cleared to make room for agricultural expansion. Ammonia (NH_4) emissions are mostly caused by rice farming, waste management, and cattle, especially through enteric fermentation.

The main sources of nitrous oxide (N_2O) emissions are soil processes including the denitrification process and, to some degree, animal dung (Gomiero *et al*., 2011; Tian *et al*., 2020).

d) Soil Erosion

One of the most important and thoroughly researched effects of agriculture is erosion of soil, which is caused by the conversion of natural ecosystems to permanent agriculture. Another is the loss of soil organic matter (SOM) (Gomiero *et al*., 2011). The amount of degraded land estimated globally varies greatly between one and six billion hectares. According to systematic assessments, by the end of 21st century most vulnerable areas for soil erosion will be semi-arid regions (Ekhout *et al.,* 2022). Approximately 40% of croplands are affected by soil erosion, with degradation observed on about one-quarter of all lands on the planet (Foley *et al*., 2005; Erb *et al.,* 2024).

Soil erosion caused by conventional agriculture poses significant challenges for ecosystems and human societies. It leads to the depletion of topsoil, a decline in soil productivity, and diminished availability of nutrients and water essential for crop growth. Furthermore, the loss of soil can lead to ecological problems including eutrophication in lakes, reservoirs, and surface waterways, which can have a detrimental effect on aquatic organisms. Moreover, it results in economic losses for farmers and a reduction in agricultural productivity (Molla *et al*., 2022).

e) Health Concerns

Conventional agriculture has raised significant health concerns stemming from the utilization of synthetic agrochemicals, such as pesticides and fertilizers, which pose detrimental effects on health of human and environment (Şener *et al*., 2020). Exposure to these chemicals can lead to allergic skin reactions, neurological effects, and even carcinogenic effects (Mie *et al*., 2017). Moreover, the use of pesticides in conventional agriculture has been associated with adverse effects on children's cognitive development (Habte and Krawinkel, 2015).

A noteworthy portion of conventional food products contains pesticide residues exceeding the maximum residue limits authorized in Europe and the USA. Consequently, a large proportion of individuals have detectable pesticide residues in their bodies, as evidenced by studies indicating that 100% of tested individuals in the USA have such residues (Girip *et al*., 2020).

f) Nitrogen leaching

Robertson *et al*. (2009) reported that Nitrogen fertilizers play a critical role in intensive conventional agriculture, yet their usage poses significant environmental concerns. Fertilizers having nitrogen are the main source of N pollution, and their use is expected to triple or almost triple by 2050.

Some dissolved nitrogen molecules, like NO_x, volatilize and contribute to greenhouse gas emissions,

whereas some dissolved nitrogen escapes deeply into underground and poses health dangers to humans. Because nitrogen oxide is the most potent greenhouse gas and the environmental problems associated with the manufacture and use of synthetic fertilizers, scientists studying pollution from nitrates and worldwide environmental change must act quickly to evaluate reduction measures (Gomiero *et al*., 2011; Liu *et al*., 2025).

3: NEED FOR SUSTAINABLE AGRICULTURE IN THE ERA OF GLOBAL POPULATION GROWTH

The projected increase in the population of world to nearly 9 billion by 2050 highlights the immense demand for food production. Addressing the challenges of sustainably meeting this demand amidst a growing population, decreasing available land due to urbanization, and global environmental changes, without compromising the needs of future generations, necessitates a comprehensive understanding of both natural and human-driven systems involved in food production and consumption (Sayara *et al*., 2016).

The concept of sustainable agriculture, as outlined by Wes Jackson in his publication "New Roots for Agriculture" in 1980, serves as the foundational framework for addressing these challenges (Gomiero *et al*., 2011). With the goal of imitating natural ecosystems, this farming method has given rise to several associated terms and activities, including precision agriculture (Sanyolu and Sadowski, 2024), low-input farming and agricultural ecology (Pretty *et al*., 2006).

In recent decades, the concept of "sustainable intensification" has emerged as a response to the difficulty of feeding nine billion people by 2050. This approach involves increasing food production from existing land while minimizing environmental impacts (Godfray *et al*., 2010; Pandey and Mishra, 2024).

Two major challenges facing the world today are the growing global population and climate change, both of which have significant implications for food availability and the sustainable use of resources. Addressing these challenges requires a fundamental shift in agricultural practices towards greater efficiency and environmental sustainability (Gonnella and Renna, 2021).

To meet the needs of the world's expanding population sustainably, agricultural methods must evolve (AlShrouf, 2017). One innovative and sustainable farming practice is hydroponics (Sousa 2024), which has been adopted by many countries, with Latin America, Brazil, and Mexico being notable users (Croft *et al*., 2017).

4: HYDROPONICS

Over time, hydroponics has evolved into a well-established branch of agronomy, with results from various countries demonstrating its practicality and advantages over conventional methods. One of its major benefits is the potential for significantly higher yields, making it suitable for areas where traditional land-based agriculture is impractical or impossible (Polycarpou *et al*., 2005; Rajasegar *et al*., 2023). Additionally, hydroponics enables better control of water, fertilizers, climate, and pest factors, resulting in increased productivity and economic returns. Plants grown using hydroponics consistently exhibit high quality, rapid growth, and enhanced nutrient content (Barman *et al*., 2016).

This method is especially beneficial in areas with restricted land access or contaminated, degraded, infertile, or unsuitable soils for agriculture. Therefore,

hydroponics is well-suited for urban areas or regions with adverse pedoclimatic conditions not conducive to traditional farming (Salas *et al*., 2012). It could serve as a solution to several challenges facing agriculture today and in the future, including dwindling arable land, water scarcity, and climate change (Szekely and Jijakli, 2022).

5: CIRCULATION SYSTEMS IN HYDROPONICS

Two primary groups can be distinguished among hydroponic systems: open systems and closed systems.

i) Open systems

The roots of open systems are either constantly or intermittently exposed to the nutrient solution. Usually, the substrate medium and nutrient solution are utilized just once and are not recycled. Open systems offer advantages such as simplified nutrient application and reduced risk of plant infection (Cifuentes-Torres *et al*., 2021).

ii) Closed systems

In closed hydroponic systems, nutrient solutions circulate from reservoir to plant roots, optimizing water and nutrient usage. Most hydroponic setups operate this way, with plants grown in either liquid or solid mediums, like organic (sawdust, coconut fiber) or inorganic (sand, gravel). However, a significant drawback is the reliance on electricity for powering pumps and other essential components (Cifuentes-Torres *et al*., 2021).

5.1: CULTIVATION TECHNIQUES OF HYDROPONICS

Because hydroponics does not require soil for food growing, it differs from conventional methods of agriculture (Figure 1). Rather, plants are grown on artificial or natural substrates, which enable their roots to effectively take up nutrients from a nutrition solution that has been carefully made. There are several ways to use hydroponics to raise food, with their selection influenced by factors such as the type of plant, local climate conditions, available budget, and other pertinent considerations.

There are a few common types of hydroponics as described below and in figure 2.

5.2: NUTRIENT FILM TECHNIQUE

The Nutrient Film Technique (NFT) is like a floating root system but with a key distinction: plant roots aren't fully submerged. Instead, they're exposed to a continuous liquid stream flowing through pipes. Although NFT uses less nutrient solution than floating root systems, it demands extra energy and components. Excess solution is returned to the storage tank by gravity, and the flow can be continuous or intermittent (Velazquez-Gonzalez *et al*., 2022).

5.3: DRIP IRRIGATION

This approach is ideal for crops like tomatoes and peppers. Nutrient solution is pumped to plant roots at a controlled rate, delivered at set intervals. In closed systems, any surplus solution is returned to the storage tank for recirculation (Velazquez-Gonzalez *et al*., 2022).

5.4: AQUAPONICS

This technique harnesses the symbiotic relationship between plants and fish to create an efficient system, where fish waste provides the necessary nutrients for plant growth. Water from the fish tank is recycled through microbial processes including nitrification and denitrification and plant consumption of nutrients,

resulting in the creation of a balanced micro-ecosystem (Velazquez-Gonzalez *et al*., 2022).

5.5: DEEP-WATER CULTURE

A platform where crops are grown plus an aeration and pumping system make up the deep-water culture system, which was a model for many modern hydroponic systems. Continuous aeration ensures that plant roots remain submerged in the nutrient solution. Monitoring and controlling oxygen concentration, conductivity, and pH levels are crucial for optimizing plant growth. This system can be adapted for use with either open or closed circulation setups (Cifuentes-Torres *et al*., 2021).

5.6: MEDIA BED-BASED CULTURE

In this system, crops are periodically flooded with nutrient solutions in a tank of substrate before draining. Continuous monitoring is essential to prevent plant dehydration. However, there's a risk of rapid spread of diseases among the roots. (Cifuentes-Torres *et al*., 2021).

5.7: WICK OR PASSIVE SYSTEM

This cost-effective system doesn't recycle nutrient solutions. Instead, it relies on capillary action in roots and fibers to deliver water to plants. It's mainly used in small-scale production but isn't ideal for long-life crops. It can be set up with open or closed circulation (Nikolić *et al*., 2026).

5.8: EBB AND FLOW (E&F) SYSTEM

This system mimics tidal patterns, with a "flow" phase where water rises in the root zone, and an "ebb" phase where it drains. Roots are periodically submerged in water from a supply tank, then partially dry out before being submerged again in cycles. Typically, inert mediums like gravel or Rockwool anchor plant roots. Oxygenation isn't needed during the dry intervals (Nikolić *et al*., 2026; Bunyuth and Mardy, 2024).

5.9: AEROPONICS

Aeroponics is a recent innovation where plants are grown above a chamber, their roots suspended while a mist of nutrient solution is sprayed. This method enhances root zone oxygenation, potentially reducing disease susceptibility and promoting finer feeding roots. It's more complex than traditional hydroponics and faces challenges like preventing nozzle blockages. Recent advances include mist generation by vibration plates and finer mists called 'fogponics'. Without water flows, monitoring and adjustment are more precise but come with added costs (Wootton-Beard, 2019; Licastro *et al*., 2024).

5.10: VERTICAL SYSTEMS

Vertical systems integrate various technologies, including those mentioned above, by employing drip irrigation across multiple layers or utilizing stacked shelving with plants receiving artificial light to offset shading from upper layers. Cutting-edge systems are becoming factory-style indoor growing setups for certain crops that are available throughout the year. Vertical systems can be erected in unusual places, such as vacant properties, and maximize space efficiency (Wootton-Beard, 2019).

MERITS OF HYDROPONICS

a) Improved Quality

It is now feasible to enhance the quality of fruits and vegetables through the application of eco-friendly methods like hydroponics. This technique is widely employed in controlled agriculture settings to manage environmental conditions and mitigate uncertainties related to soil water and nutrient levels. Furthermore,

the nutritional makeup of fruits and vegetables can be influenced by exact control over temperature and light. A statistical analysis has demonstrated a significant difference in the quality of production between lettuces grown hydroponically and conventionally. Studies have indicated that tomatoes grown in soil-less culture systems exhibit superior attributes such as taste, acidity, vitamins, and carotenoid content (Barman *et al*., 2016).

a) Cost Efficacy

Hydroponics stands out as an exceptionally lucrative and rapidly expanding cultivation method within the agriculture sector. It offers a remarkably clean and straightforward approach, devoid of risks associated with soil-borne diseases, insect infestations, or pest infections (Hussain *et al*., 2014). Consequently, hydroponics yields exceptionally healthy crops with high productivity within a short timeframe, while operational expenses remain notably lower compared to soil-based cultivation methods.

In contrast, soil-based cultivation entails growing crops in open fields with irrigation, necessitating significant applications of fertilizers, pesticides, and herbicides to foster crop growth. Consequently, the production rate and yield quality are comparatively diminished. However, hydroponic systems eliminate such risks, ensuring high production rates. Commercial cultivars, including roses and various vegetables such as tomatoes, lettuces, cucumbers, strawberries, and numerous other crops, thrive successfully at a reduced cost. Overall, soil-less culture facilitates efficient nutrient regulation, resulting in increased production at a lower cost (Chatterjee *et al*., 2025).

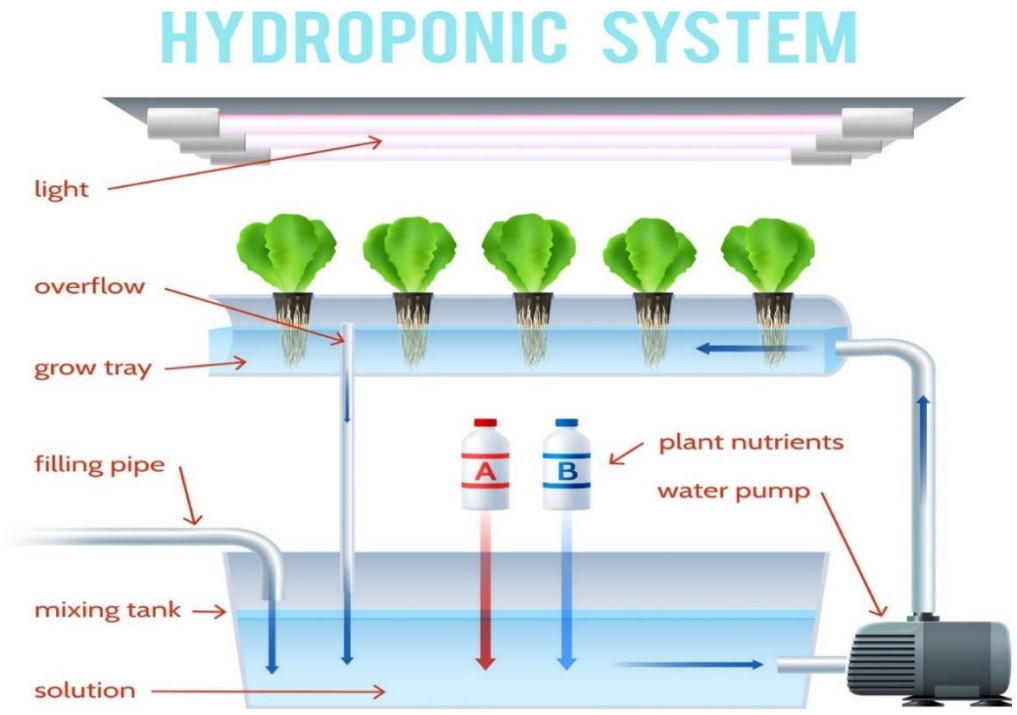

Figure 1: Basic Hydroponics

b) Faster Growth Rates

Pandey *et al*. (2009) stated that provided with precisely what it requires and when it's needed, a plant is poised to thrive to its fullest genetic potential. This ideal scenario is precisely achievable in hydroponics, where the creation of an artificial environment within enclosed spaces, facilitated by elements like lightning and air conditioning, ensures optimal conditions for plant growth (Jan *et al*., 2020). In this setup, plant growth is expedited, as roots encounter no mechanical barriers and all necessary nutrient elements are abundantly available.

Water conservation emerges as a paramount advantage of hydroponics. It drastically reduces water consumption, utilizing as little as $1/20^{th}$ of the water compared to traditional farming methods to yield equivalent food output. The risk of waterlogging is entirely mitigated in hydroponic systems. For instance, the production of one kilogram of lush green fodder necessitates merely 2-3 liters of water, a stark contrast to the 60-80 liters required in conventional fodder production systems (Jan *et al*., 2020).

c) Space Efficiency

Implemented vertically, the method also proves to be space-efficient, enabling year-round production within climate-controlled greenhouses (Velazquez-Gonzalez *et al*., 2022). In contrast to traditional farming, Van Delden *et al*. (2021) stated that hydroponics maximizes yield by not just making use of horizontal surface areas but also making the most of the overhead vertical space. By increasing the density of plants per unit area, this technique contributes to the growing trend of vertical gardening, which aims to supply fresh, wholesome food to areas with high populations. Consequently, hydroponics demands less space to yield the same amount of crop as field cultivation (Pandey *et al*., 2009).

d) Reduced need for pesticides

Because hydroponic systems don't require soil, they lessen the chance of soil-borne diseases and pests, which reduces the need for pesticides and herbicides (Pandey *et al*., 2009). Conversely, in geoponics, farmers often resort to fertilizers and pesticides to enhance crop quality, resulting in produce that may not be organic and may contain medications, thus compromising its quality. Such issues are circumvented in hydroponics because there's no need for farmers to add fertilizers to the nutrient-rich water; instead, crops extract necessary minerals directly. Additionally, studies have shown that hydroponically grown greens are superior in taste. Consequently, this represents another domain where hydroponics outperforms geoponics (Velazquez-Gonzalez *et al*., 2022).

e) Surplus and scarcity

As urbanization continues to accelerate, the already limited land becomes increasingly scarce, leaving people with inadequate space in cities. Moreover, the burgeoning urban population escalates the demand for food, leading to what Mike Segar from Reuters has termed as "People are hungry everywhere." This starkly highlights the disparity between food demand and supply, underscoring the critical need to address food shortages. In such a scenario, traditional geoponics, reliant on vast expanses of land, appear increasingly impractical. Consequently, there's a growing trend towards embracing hydroponics as a

Received: 04-04-2026, **Accepted**: 20-07-2026, **Published**: 15-08-2026
Citation: Shahid T, Javed F, Anmol A, Afzal S (2026). Nano-enabled hydroponics: The intersection of precision agriculture and nanobiotechnology. Nanobotanica, 1(1), 36-48.
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solution, leveraging its ability to cultivate crops in relatively smaller spaces (Jan *et al*., 2020).

f) Fodder quality

In comparison to conventionally produced green forage, hydroponic green forage exhibits an increase in crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), and calcium (Ca) content, while organic matter (OM) and non-fibrous carbohydrates (NFC) content decrease. Additionally, hydroponic fodder serves as a significant reservoir of essential nutrients including vitamin A, vitamin E, vitamin C, thiamin, riboflavin, niacin, biotin, free folic acid, and antioxidants such as β-carotene, alongside various minerals. Additionally, hydroponic feed has an abundance of beneficial enzymes (Jan *et al*., 2020).

g) Decreased need for labor

Long-term, hard work is required for cultivation in the development of conventional feed. However, in hydroponics, the labor required is significantly reduced to only 2-3 hours per day (Jan *et al*., 2020).

6: NANOTECHNOLOGY AND HYDROPONICS TECHNIQUE

The fusion of Nanotechnology and Hydroponics brings forth the concept of "smart agriculture." This entails the utilization of nanofertilizers, commonly known as "smart fertilizers," which optimize nutrient delivery, resulting in improved plant growth and higher yields (Dayma *et al*., 2023).

Malik *et al*. (2023) reported that nanotechnology has steadily pervaded various industries worldwide, showcasing a rapid technological revolution, particularly in developed nations markets based on nanotechnology have thrived in recent years. These materials are finding applications across interdisciplinary scientific fields, including active and passive nano-assemblies, general nano-systems, and small-scale molecular nano-systems.

In agriculture, nanotechnology plays a pivotal role across every stage of farming, spanning from seed germination to growth, harvest, processing, storage, and transportation of agricultural products (Saritha *et al*., 2022). An emerging aspect within nanotechnology is green synthesis, characterized by its simplicity, affordability, and consistency as a technique (Azmat *et al*., 2022).

6.1: APPLICATION OF NANOPARTICLES IN HYDROPONICS

Nanoparticles have emerged as a promising tool to enhance the efficiency and sustainability of hydroponic systems. Due to their extremely small size and high surface area, nanoparticles can improve the availability and uptake of essential nutrients by plant roots. In hydroponics, where nutrients are supplied directly through solution, nano-sized fertilizers such as zinc oxide, iron oxide, and silica nanoparticles can provide a more controlled and targeted delivery. This results in improved nutrient use efficiency, reduced wastage, and enhanced plant growth and productivity compared to conventional fertilizers (Jadoon *et al*., 2024).

Another important application of nanoparticles in hydroponics is their role in improving plant stress tolerance. Plants grown in hydroponic systems may face abiotic stresses such as salinity, heavy metal toxicity, and oxidative stress. Nanoparticles, including silicon, selenium, and titanium dioxide, have been reported to enhance antioxidant defense systems, regulate osmolyte accumulation, and reduce the generation of reactive oxygen species.

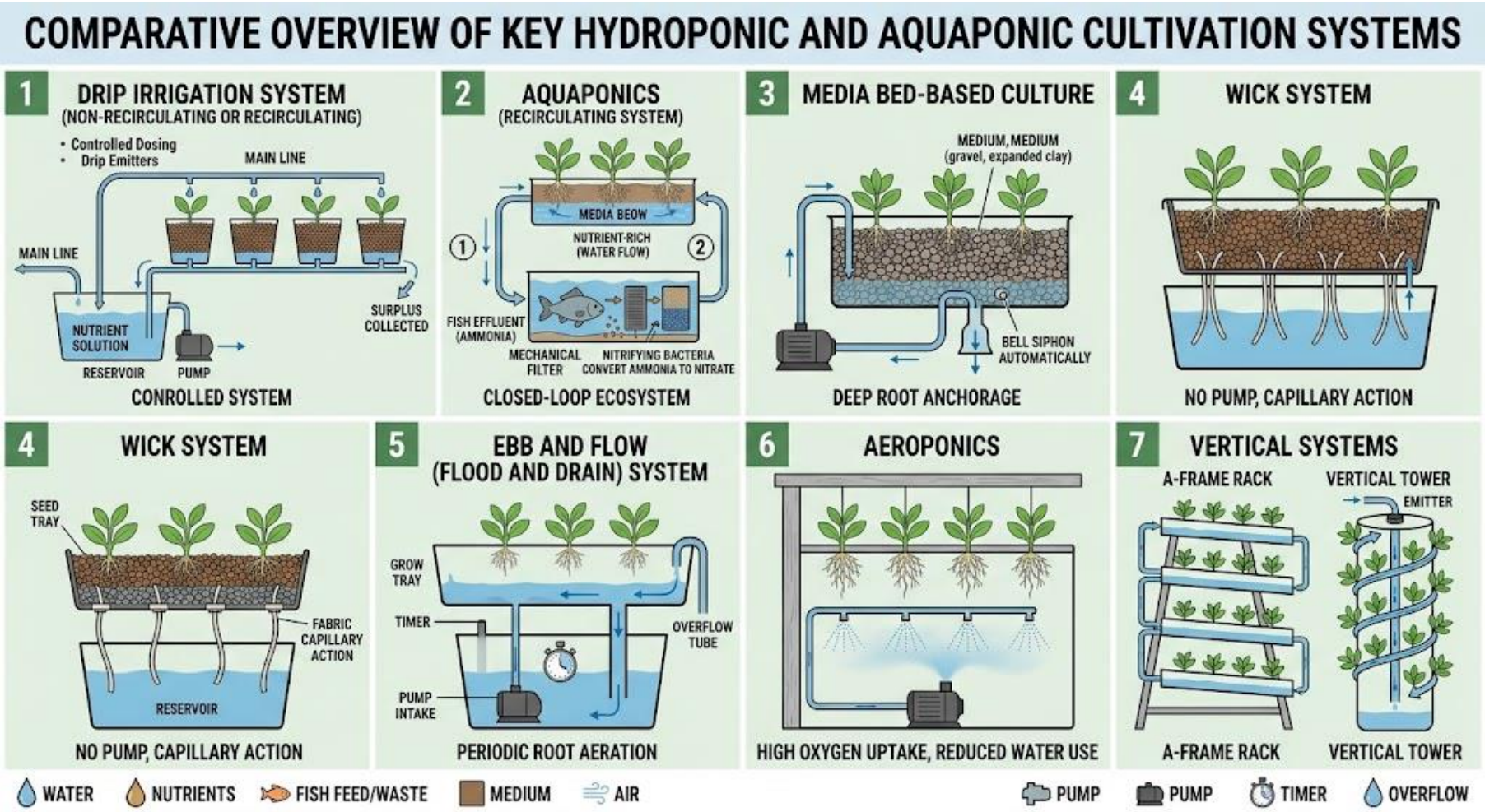

Figure 2: Types of Hydroponics

This leads to improved plant resilience, better physiological performance, and higher yields even under suboptimal growing conditions (Zhao *et al*., 2020).

Nanoparticles also play a significant role in disease management and microbial control in hydroponic systems. The closed nature of hydroponics makes it susceptible to rapid spread of pathogens. Metal and metal oxide nanoparticles such as silver, copper, and zinc oxide exhibit strong antimicrobial properties, helping to control bacterial and fungal infections in nutrient solutions. Additionally, nanoparticles can be used in the development of nanosensors for real-time monitoring of nutrient levels, pH, and contaminants, thereby improving system management and precision agriculture practices (Elmer *et al*., 2018).

Furthermore, the integration of nanoparticles in hydroponics contributes to environmental sustainability. By reducing the excessive use of chemical fertilizers and pesticides, nanoparticle-based inputs minimize nutrient runoff and environmental pollution. Their controlled release properties ensure efficient utilization of resources, making hydroponic systems more eco-friendly. However, it is also important to consider the potential risks associated with nanoparticle accumulation and toxicity, highlighting the need for careful dosage optimization and further research to ensure safe and sustainable applications (Jadoon *et al*., 2024).

6.3: MECHANISM OF UPTAKE AND TRANSPORT OF NANOPARTICLES,

Tripathi *et al*. (2017) explained a complicated chain of events occur when nanoparticles enter plant roots, vascular bundles (xylem) and stele are eventually reached by nanoparticles, which penetrate the root epidermis through the cell membrane and cell wall. Eventually, the nanoparticles reach the leaves.

According to Judy *et al*. (2012), nanoparticles passively incorporate through the apoplast of the endodermis to reach the stele. Together with other cellular functions including recycling, signaling, and plasma membrane control, active transport makes up the majority of the absorption mechanism (Tripathi *et al*., 2017). Nanoparticles enter the plant root through various mechanisms, including osmotic pressure, capillary forces, and pores on the cell wall via plasmodesmatal connections and/or symplastic pathways (Gao *et al*., 2011). After entering a plant cell, nanoparticles can move across cells via plasmodesmata and the apoplast or symplast (Hauck *et al*., 2008; Azim *et al*., 2023).

The pore size of the cell wall determines the entry of nanoparticles across it; tiny particles can pass through more readily than larger ones. Larger nanoparticles can enter plants through stomata, hydathodes, and flower stigma, accumulating in stomata for translocation via the phloem. They can also penetrate the seed coat's intercellular spaces, regulated by aquaporins. (Usman *et al*., 2020; Rehman *et al*., 2026).

7: NANOTOXICITY

Nanotoxicity is a major issue of hydroponics. If NPs cross their threshold, they can cause severe oxidative stress to the root cells and cause overall stunted growth of plants. nanoparticles can also damage the root surface directly causing root cell damage and root tip shrinkage. These can also damage cell DNA, proteins and other essential biochemicals by producing excessive ROS. These NPs in toxic quantities can cause metabolic disruptions like slower photosynthesis and respiration etc. These can also cause ionic disbalance inside the plant cell. Toxicity

levels of NPs may be influenced by plant species, P type, NP concentration, NP size, NP shape, or type of hydroponic technique being used. But such issues can be resolved by integrating hydroponics with AI tools. AI tools can control the release of NPs in the liquid medium as per pre-described doses (Djanaguiraman *et al*., 2024).

CONCLUSION

In conclusion, hydroponic systems, including nutrient film techniques (NFT), deep water culture (DWC), aeroponics, and drip-based systems, offer remarkable flexibility for modern agriculture by enabling precise control over nutrient delivery, water use, and environmental conditions. This adaptability allows growers to tailor production systems to specific crops, space constraints, and climatic challenges. The integration of nanoparticles further enhances these systems by improving nutrient use efficiency, promoting plant growth, and strengthening stress tolerance, thereby making hydroponics more productive and resource efficient. In parallel, the emergence of nanosensors for real-time monitoring of nutrient status, pH, and plant health represents a significant advancement toward precision agriculture. Together, these innovations indicate a future where hydroponics, supported by nanotechnology, can contribute substantially to sustainable, high-yield, and smart agricultural practices.

8: DECLARATIONS:

FUNDING: Not applicable.

CONFLICT OF INTEREST: The authors declare no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS: Not applicable.

CODE AVAILABILITY: Not applicable.

AUTHOR CONTRIBUTIONS: All authors contributed equally with no conflict of interest.

ETHICAL APPROVAL: Not applicable.

AI USAGE: Figures were made by using chatGPT and proper prompts with instructions were given to the AI tool for this purpose.

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