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"A review on the development of innovative hydroponics designs for modern living spaces"

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Abstract: *Hydroponics is a sophisticated and eco-friendly farming practice in which plants are grown without soil but using nutrient-rich water solutions under controlled growing environments. Due to increasing population, limited agricultural lands, drought conditions, and climate change, hydroponic cultivation has achieved broad interest as an innovative strategy to ordinary or traditional agriculture. This review article provides an overview of the principal hydroponic methods and their working mechanism based on findings reported by various scientists. Different hydroponic approaches, comprising Nutrient Film Technique (NFT), Deep Flow Technique (DFT), drip system, ebb and flow system, and aeroponics, have been evaluated based on their working principles, benefits, limitations, and crop compatibility. The review also emphasizes innovative hydroponic designs such as vertical, horizontal, indoor, outdoor, and various design systems constructed for well-organized space optimization and elevated crop production efficiency. Various experiments conducted by various researchers on the selection of compatible plant varieties for hydroponic farming have been reviewed. In addition, important factors impacting plant growth, consisting of growing media, nutrient solution composition, pH, electrical conductivity (EC), and total dissolved solids (TDS) regulation, are extensively assessed. Broadly, hydroponic technology indicates significant capacity for renewable and future-focused agriculture by enabling throughout the year production, efficient water utilization, reduced reliance on soil, and enhanced crop performance. The review emphasizes the significance of advanced agriculture systems as a promising and sustainable solution for global food sustainability and urban cultivation systems.*
Key words: *Hydroponics, Indoor Farming, Aeroponics, Vertical Farming, Aquaponics, Sustainable Agriculture, Urban Agriculture*

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I. Introduction:

Hydroponics is a technique of growing plants without soil by supplying nutrient-rich solutions, intermittently aided by non-reacting materials like rockwool and coconut fibre. The term was introduced by Professor William Gericke in the 1930s. It is also known as tank farming culture (Kothal *et al*., n.d.). Hydroponics is the method of cultivating plants in various mediums like sand, water, etc. by use of nutrient solution with no soil (Savvas *et al*., 2003) and (Douglas *et al*., 1975). It facilitates accurate control of water, nutrients and light for plant growth (Sharma *et al*., 2018). Hydroponics has been authorised as a viable technique of cultivating vegetables like lettuce and cucumber as well as ornamental plants. Frequently used growing mediums consist of vermiculite and wood fibre (Shrestha & Dunn *et al.,* 2010). Hydroponic setups are divided as open (nutrient solution is used once) or closed (nutrient solutions can be recycled). Different systems, like liquid systems, are medium-free; aggregate systems have a solid medium of support (Jensen *et al.,* 1997). Sometimes, soil has some unfavourable effects on plant growth, like the presence of nematodes and pathogens, soil erosion, less fertility, etc. So, open-field agriculture is a bit difficult, so hydroponics can be a substitute and supportive method (Sardare *et al.,* 2013). Europe is regarded as a leading region in the hydroponics industry due to multiple factors, i.e., adoption of advanced systems. According to a report by Jensen and Collins (1985), the global hydroponic market was projected to expand at a rate of 18.8% from 2017 to 2023, acquiring an estimated value of about USD 490.50 million by 2023 (Jan & Rashid *et al*., 2020).

According to estimates by the Food and Agriculture Organization (FAO), the world's population is estimated to reach nearly nine billion, necessitating about a 70% increase in agricultural production. Urban expansion means about 75% of people live in urban areas. Although urban areas occupying only about 3% of

Earth's land surface, the global population is anticipated to rise by 2.5 billion people. At the same time, food output faces significant challenges, facing the obstacles of not only producing more food but also facing the problems of climate change and less land. Moreover, hydroponics makes it a bit easy to grow several crops in less land, with less use of water and without chaotic expulsion of hazardous fertilizers to the environment, as hydroponics allows less use of fertilizers and pesticides (Gonzalez *et al.,* 2022). A wide range of food crops has been effectively cultivated through hydroponic systems, such as leafy vegetables and culinary herbs like lettuce, tomatoes, and cucumbers. Organic hydroponics involves using natural nutrient sources to grow plants. It is also known as a biopic, a term that may furthermore refer to the integration of microorganisms in organic fertilizers (Park & Williams *et al*., 2024).

WHY HYDROPONICS?

As the population increases and land areas are lacking, the expanding requirement for food is obvious, and projections advise that crop yield must double to meet this demand (The Sahara Forest Project, 2009). It is unfortunate that agriculture remains one of the most uncertain sectors, heavily influenced by natural factors such as droughts, fires, and floods. According to the US Department of Agriculture, around 90% of crop damage is due to weather conditions (Orsini *et al*., 2013).

Hydroponics is a multi-purpose technology suitable for both evolving nations such as India and modern environments like space stations. It has been applied by NASA as a feasible method for securing a self-reliant food system for astronauts and has assisted research under the Controlled Ecological Life Support System (CELSS) program to elaborate its edge in space (Khan & Purohit *et al*., 2020). One of the earliest accomplished uses of hydroponics took place in the 1930s on Wake Island, where it was implemented to cultivate fresh vegetables for passengers of Pan American Airlines. After this first breakthrough, ongoing research was executed to boost and polish hydroponic techniques (Pandey *et al.,* 2009. This improvement played a major role in forming modern hydroponic systems. Later, Jensen and Collins (1985) provided an extensive review, depicting various new hydroponic cultivation systems built across Europe and the United States.

TYPES OF HYDROPONICS SYSTEM: -

There are several types of hydroponic systems, and each offers distinct benefits as well as certain limitations (Nguyen *et al*., 2016; Santosh *et al.,* 2023). Numerous methods are available that facilitate our modifying cultivation systems according to our particular requirements. If adequate space is available, different methods can be combined to optimize efficiency and flexibility (Yuvaraj *et al.,* 2020). Hydroponics systems are generally categorized into two groups, based on the reuse of nutrient solution: one is an open system, and the other is a closed system (Jensen *et al.,* 1999). Typically, open hydroponic systems tend to be less affected by high salinity levels in water (Seungjun Lee and Jiyoung Lee *et al.,* 2015). Different types of hydroponics include the following:

1) Deep Flow Technique (DFT): - Deep Flow Technique, also referred to as Deep Water Technique, includes growing plants on floating or elevated supports such as rafts or boards, which are placed above reservoirs grasping a 10-20 cm deep nutrient solution (Van Os *et al*., 2008; Maucieri *et al.,* 2019). The deep flow technique is a hydroponic method in which plant roots are directly immersed in a nutrient-rich solution, ensuring a constant supply of water, nutrients, and oxygen for vigorous plant growth (Nursyahid *et al.,* 2021).

2) Nutrient Film Technique (NFT): - The Nutrient Film Technique (NFT) is a hydroponic method where a thin layer of nutrient-rich solution continuously flows over the plant roots; this allows the roots to receive water, nutrients, and oxygen directly (Mashumah *et al*., 2018). The nutrient film technique provides modern and efficient strategies to support renewable agriculture (Samba *et al*., 2023). The NFT system delivered nutrient solution directly to the plant roots, so there was no need for any growing substrate (Palmitessa *et al.,* 2024).

3) Drip System: - In a drip system, a timer operates a submerged pump, which occasionally engages and supplies nutrient solution directly to the base of each plant through small irrigation lines (Shrestha and Dunn *et al.,* 2010). The drip system is commonly used in large-scale hydroponic farming for growing long-season crops such as tomatoes and cucumbers (Sheikh, 2006). A drip system uses a network of valves, pipes, and emitters to supply water directly to the plant roots. This method helps preserve water and boosts crop productivity (Al-Nawaiseh, 2025).

4) Ebb and Flow system: - One of the most commonly used hydroponic systems is the ebb and flow system (Daud and Handika *et al.,* 2018). Ebb and flow cropping systems are more productive for cultivating lettuce and other small vegetables because they permit better inspection of plant growth (Giacomelli *et al*., 1998; Kinani *et al*., 2021). Ebb and flow systems are used in automated crop production setups, varying from adjustable bench systems to heated concrete floors. They provide a uniform way to supply water, oxygen, and nutrients to plant roots, without draining the system (Giacomelli *et al*., 2019). Ebb and flow systems tend to rinse out more debris, which can reduce the amount of nutrients available for breakdown and mineralization in the growing media (Romano *et al*., 2023).

5) Aeroponics System: -An aeroponic system is an enclosed system where plant roots are suspended in air and frequently sprayed over with a nutrient-rich solution, enabling rapid growth with minimal water consumption and little direct sunlight (Kumari and Kumar 2019). Aeroponics is a method of growing plants without soil or any growing medium, where plants are assisted synthetically and roots grow in air (Lakhiar *et al*., 2018). Aeroponic systems use pumps, timers, and spray nozzles to provide a nutrient-rich mist to plant roots at regular intervals, aiding them in assimilating water and nutrients efficiently (Garzon *et al*., 2023).

DIFFERENT DESIGN MODELS OF HYDROPONIC SYSTEM

Advanced hydroponic systems are developed to conquer plant growth complications by spontaneously influencing factors like nutrients, water, and environment. This makes indoor farming viable even in small spaces (Chowdhury *et al.,* 2020). During the COVID-19 period, changing lifestyles inspire people to grow plants at home using simple hydroponic systems. They began cultivating plants in gardens, balconies, terraces, and even indoors, a part of ordinary life (Karagoz *et al.,* 2022). The study investigates different facets of decorative plants for phytoremediation and their effect on soil cleansing (Kaur *et al*., 2025). Urban expansion limits water and space for farming, so the use of flush water in domestic gardening is eliciting attention; it can serve as a substitute source of both water and nutrients for plants (Sundar *et al*., 2021). In ancient times, the Hanging Gardens of Babylon were considered to rely on hydroponic techniques to grow plants and flowers, aiding the construction of a distinct and attractive garden, and this idea subsequently propagated for decorative gardening (Kothal and Parashar, n.d.).

Some design models are included in this study to illustrate different hydroponic system structures:

Vertical hydroponic system: - Vertical hydroponic farming is evaluated as technical design strategies to optimize crop production by growing plants upward-directed in layers. This method increases production rate per unit area, enhancing land use competence for growing crops (Eigenbrod and Gruda, 2004; Touliatos *et al.,* 2016). Vertical urban farming mainly relies on controlled environments. These systems use LED lighting, hydroponic nets, controlled atmosphere, and hydroponics, making them partially resistant to climate change as they are portable (Martin *et al*., 2019). Vertical farming is still in the beginning phase of technological development, but it has substantial potential to play an important role in the future of urban cities (Nerantzis *et al*., 2018). Vertical farming has recently drawn attention as an effective substitute method for growing vegetables (Reddy *et al*., 2022). It supports renewable urban development, food assurance, and better health (Gumisiriza *et al*., 2022).

Horizontal hydroponic system: - Horizontal hydroponic systems are well known in cities for their competent space use and enhanced productivity. Lettuce and strawberry plants were used to correlate horizontal and vertical growing systems. Vertical systems gave more strawberry yield per area, while horizontal systems produced heavier lettuce and a higher tradeable percentage (Neocleous *et al*., 2010).

Indoor hydroponic systems: - Growing plants and vegetables in distant areas like deserts or polar areas is complex due to harsh and severe climate conditions. In this project, Palande *et al*. (2018) developed a system that observes and monitors all the essential conditions required for healthy indoor plant growth. When it comes to vegetable cultivation, not every area is adequate for growing them outdoors (Nikolov *et al*., 2023). Another study reported the advancement of a small indoor hydroponic vegetable system for domestic use that applies sustainable energy sources such as solar, wind, and hydrogen power (Yamaguchi *et al*., 2018). Hydroponics can be conducted indoors by using artificial LED light instead of natural sunlight. The University of Wisconsin proposed using LEDs for crop growth, where different light colors can be directed to influence heat intensity (Atmadja *et al.,* 2022). Urban agriculture comprises cultivating everyday plants such as vegetables, mushrooms, fruits, and ornamental plants. In recent times, indoor hydroponic methods in urban farming have gained significant attention (Niswar, 2024).

Outdoor Hydroponic system: - Hydroponics acquired importance in a short time, which encouraged people to start growing plants using this method both inside and outside (Mariyappillai *et al*., 2020). In another study, the researchers evolved an IoT-based system to track greenhouse conditions. It uses two nodes: one device gathers data and sends it to another (sink node), which then conveys the information to a management center using SMS (Edwin *et al.,* 2022). A study reported that rooftop horticulture means growing plants on top of buildings. As many roofs are vacant, they can be used to grow crops and offer a significant portion of vegetables for residents (Ezziddine *et al*., 2021). Liu *et al*. reported that they successfully harvested seven types of leafy vegetables using hydroponic systems on rooftops (Liu, Ting, *et al*., 2016). As the population grows, we need to yield more food while minimizing harmful pesticides. A smart greenhouse is a solution because it increases production without using pesticides (Andrianto et *al*., 2020).

Hanging bags system: - The bag system is a greenhouse method where plants are grown in disposable bags filled with a growing medium, which are organized in rows inside a greenhouse. Bags are modelled from UV-protected plastic and can be used for around two years (Marr and Charles, 1994). This approach, also called the verti-grow technique, utilizes suspended bags where plants are placed in holes long their sides allowing vertical growth. The nutrient solution is conveyed to the top of each hanging bag using a micro-sprinkler fixed inside, enabling it to descend and feed the plants (Goswami et *al*., 2022).

Net pot system: - This method grows different types of lettuce in tanks filled with nutrient water, doesn’t require electricity or pumps, and plants in net pots are positioned in holes on a cover above the tank (Kratky, 2010). Plants can be grown in suspended pots using a nutrient solution, and the whole crop can grow with just one filling of nutrients (Shah *et al*., 2011).

II. METHODOLOGY: -

➢ **Selection of plant species in different hydroponic systems: -** Different researchers designated different plant species in their studies and used several hydroponic techniques. A study was proposed to cultivate tomato varieties appropriate for vertical vegetable cultivation using multi-tier hydroponic systems. A total of 696 tomato samples were used as the research material. The study methods comprised evolving a model for a new type of tomato suitable for multi-tier hydroponic systems to grow vertically and studying the genetic factors responsible for the “short height” trait in tomato plants (*Solanum lycopersicum L.)* (Balashova *et al*., 2019). A vertical garden was developed using 32 different ornamental plant varieties, mainly constituting decorative foliage plant species, including *Asplenium thunbergii, Alocasia sanderiana, Anthurium crystallinum*, etc., as reported by Phonpho and Saetiew (2017). Senanunsakul (1997) determined Cantaloupe grown using the nutrient film technique hydroponic system under a specially customized slanted-roof shed had an assessable average fruit weight (Wiangsamut *et al*., 2017). *Lactuca sativa* (lettuce) is a widely consumed leafy vegetable (Al-Kinani *et al*., 2021). Ebb and flow cropping systems are more efficient for growing lettuce and other small vegetables, as they enable better monitoring of plant growth (Giacomelli *et al*., 1998). Lettuce cultivation is water-efficient, as it needs only a limited amount of water (Al-kinani *et al.,* 2021). Baby spinach (Spinacia oleracea) was grown in a small-scale deep-water culture (DWC) system using extended polystyrene (EPS) plug trays, as stated by Janeczko *et al*. (2019). Another experiment was executed using an adjusted DFT (Deep Film Technique) hydroponic system with PVC pipes to evaluate growth, yield, and water use of coriander (*Coriandrum sativum*) by Silva *et al*. (2018). The Australian greenhouse industry is largely prevalent with low-cost hydroponic systems that supply water and nutrients to grow vegetables like cucumber (*Cucumis sativus*) and tomato (*Solanum lycopersicum L.), as* reported by Grewal *et al*. (2011).

➢ **Growing media: -** Various types of growing media used by different researchers, as shown in the table below.

Table no 1: Shows various types of growing media used by different scientists.

S. No.	Growing media	References
1.	A study shows that several growing media like coco peat, sawdust, rice husk, perlite, and sand have been used and also tested different media aggregations for crop suitability.	(Patil *et al*., 2020)
2.	Three different growing media were used: sawdust, cocopeat, and sterilized absorbent cotton.	(Gaikwad *et al*., 2020)
3.	Three hydroponic systems were used as main plots: elevated tray, ground-level bed, and bag culture systems. The subplots included three different media components: sawdust, river sand, and vermiculite.	(Wahome, *et al*., 2011)
4.	Cocopeat, sponge, and perlite are used to cultivate lettuce.	(Chhetri *et al*., 2022)
5.	Gerbera (*Gerbera jamesonii*) is an herbaceous plant that is grown in a hydroponic system in various types of growing media such as perlite, rock wool, vermiculite, sand, coco peat, expanded clay, organic substrates, cow compost, zeolite, pumice, etc.	(Khalaj *et al*., 2011)
6.	Common natural organic media include peat, coconut coir, wood fiber, bark, sawdust, and composted plant waste. Inorganic media: pumice, perlite, zeolite, vermiculite, expanded clay, rockwool, and sand. Synthetic organic media: polyurethane, urea-formaldehyde foams, and polyester fibres.	(Kennard *et al*., 2020)
7.	Different media were used to cultivate strawberries with different chemical and physical properties. These media can also be mixed in different ratios for better results. For example, one study found the highest yield with 100% rice husk, while others reported that a mix of perlite (60-80%) and peat (20-40%) gives the best growth and yield in strawberry.	(Wortman *et al*., 2016)

➢ **Nutrient Solution: -** Nutrient solution and its regulation are the substructure of a successful hydroponic system, as it directly influences crop yield and quality. Nutrients must be delivered in well-balanced proportions according to the plant’s requirements (Al Meselmani, 2022). Hydroponics usually relies on mineral fertilizers to prepare the nutrient solution. Liquid organic fertilizers are nutrient-rich solutions made from organic sources, diluted with water, and used in hydroponic systems in elaborate forms. They must first be disintegrated by microbes through decomposition and mineralization into simpler forms that plants can take easily (Szekely and Jijakli, 2022). Proper administration of nutrient solutions in hydroponics depends on sustaining proper pH, electrical conductivity (EC), and ion concentration (Rijck and Schrevens, 1995). Among those, pH is particularly important because it influences nutrient accessibility, solubility, and uptake by plants. The suitable pH range is 5.5-6.5, where nutrients are most easily convenient for plant growth (Fathidarehnihej *et al*., 2023).

- **Element composition of nutrient solution: -** Elements composition of nutrient solution is mentioned below the table:

Table no 2: Shows nutrient solution composition.

Element	Form taken up by plants	Hoagland and Arnon	Hewitt	Copper	Steiner
Nitrogen	NH4+, NO3-	210	168	200-236	168
Magnesium	Mg2+	34	36	50	48
Copper	Cu2+	0.02	0.064	0.1	0.02
Phosphorus	H2PO4-	31	41	60	31
Potassium	K+	234	156	300	273
Iron	Fe2+, Fe3+	2.5	2.8	12	2-4
Calcium	Ca2+	160	160	170-185	180

Table 2. Nutrient forms absorbed by plants and recommended nutrient solutions by different scientists.
Source of table 2- (Meselmani *et al*., 2022; Salisbury and Ross; Cooper; Steiner; Windsor and Schwarz; Hoagland and Arnon; Hewitt).

- **Optimum pH and Electrical Conductivity of some plants: -**

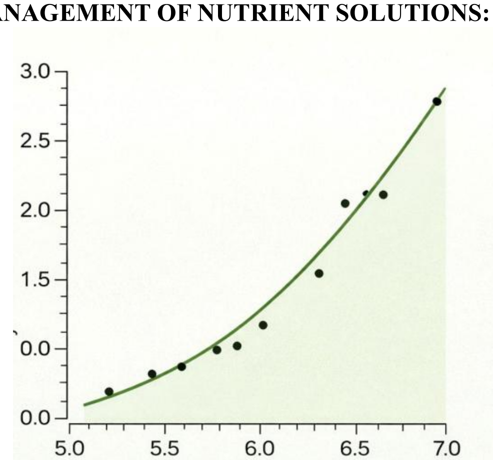
Table no 3: Shows Optimum pH and EC

S.NO.	Plants	pH	EC
1.	Cauliflower	6.0-6.5	0.5-2.0
2.	Peppers	5.5-6.5	2.0-3.0
3.	Tomato	5.5-6.5	2.0-5.0
4.	Broccoli	5.5-6.5	2.8-3.5
5.	Spinach	5.5-6.5	1.8-2.3
6.	Banana	5.8-6.5	1.8-2.2
7.	Cucumber	5.5-6.5	1.7-2.0
8.	Egg plant	5.5-7.5	2.5-3.5

Source of table 3- Optimum pH and EC of some plants: Mehboob *et al*., 2019; Meselmani *et al*., 2022.

MANAGEMENT OF NUTRIENT SOLUTIONS: -

HCO_3 Concentration



pH of nutrient solution

Figure 9. Scatter diagram showing relationship between pH of nutrient solution and bicarbonate concentration.
Source: - (Savvas *et al*., 1999)

Table no 4: Shows solubility of oxygen in pure water at various temperatures.

Temperature	Oxygen Solubility (mg L^{-1})
10	11.29
15	10.08
20	9.09
25	8.26
30	7.56
35	6.95
40	6.41
45	5.93

Source of table 4**- Meselmani *et al*., 2022**

➢ **Importance and Challenges: -** Indoor vertical farming started coming into focus around 1999, but a few commercial agriculture units have succeeded so far. Some of the well-known examples include AeroFarms, Sky Greens, and Vertical Harvest. Even today, this technology is still new, so it's uncertain regardless of whether it will be achieved worldwide successfully economically or socially. Financial constraints are a major issue. Large-scale farms tend to show better outcomes, often supported by government incentives and funding. Its long-term success and impact—especially on small farmers—are yet uncertain (Ampim *et al*., 2022). Future agrifood systems should focus on renewability by compressing environmental impact, enhancing product output, shielding natural resources, preventing pollution, preventing food waste, and lowering energy use—especially reliance on fossil fuels (Sousa *et al*., 2024). Hydroponic systems use only about 10% of the water compared to conventional or traditional farming, reducing total water use by over 75%. Although the preliminary arrangement cost can be up to ten times higher, these systems provide detailed management over plant nutrition since roots are directly revealed to the nutrient solution. For proper persistent plant growth, it is important to properly check and manage factors such as humidity, pH, electrical conductivity (EC), surrounding temperature, and the water level in the container (Chowdhury *et al*., 2020).

➢ **Advantages of hydroponic systems: -** Hydroponic systems grant various positive effects compared to traditional soil-based cultivation.

✓ They can be successfully used in regions where soil is inappropriate for crop yield due to corruption by hazardous materials or heavy metals (Lee *et al*., 2015).

✓ Along with this, indoor hydroponic setups allow precise control over growth conditions, comprising temperature, water flow rate, nutrient supply, and relative humidity (Lee *et al*., 2015).

✓ Hydroponic technology allows rapid plant growth while using less water and land, and it develops healthy, consistent, and high-quality yield. This method minimizes carbon emissions and eradicates the need for pesticides (Bunyuth *et al*., 2024).

✓ Water saving is one of the major advantages of hydroponic systems, making them ideal for regions with limited water availability (Khatri *et al*., 2024).

➢ **Limitations of hydroponic systems: -** There are some limitations of hydroponic systems, which are given below: -

✓ Setting up a hydroponic system involves a high primary investment. Expenditures involve materials like grow trays, reservoirs, pumps, and support structures. In addition, costs are involved in creating an artificial environment, such as a greenhouse or indoor growing spaces with climate control systems (Khatri *et al*., 2024).

✓ Hydroponic systems desire innovative technology and consistent maintenance, making them less favorable for beginners (Santosh *et al*., 2023).

✓ A steady supply of lighting and energy is crucial for secure functioning of hydroponic systems. Monitoring proper EC, pH, and the optimal nutrient concentration is also mandatory. In addition, environmental conditions in indoor hydroponic systems such as temperature, light intensity, carbon dioxide levels, and humidity need to be constantly monitored (Ghorbel *et al*., 2022).

✓ Since all plants in a hydroponic system use the same nutrient solution, any disease or pest can rapidly scatter and affect the total crop production (Pandey *et al*., 2009).

III. Conclusion

Hydroponics has appeared as an encouraging and renewable alternative to traditional soil-based agriculture, especially with regard to rapid urbanization, limited land accessibility, water crisis, and increasing food demand. This review focuses on those hydroponic systems that allow proper utilization of resources by considerably reducing water consumption, maximizing nutrient delivery, and allowing cultivation in controlled or artificial environments. Different systems such as DFT, NFT, drip, ebb and flow, and aeroponics offer versatility to cultivators depending on crop type, space, and economic conditions. Advanced innovations, including vertical farming and indoor hydroponic designs, illustrate high prospects for urban food production and smart agriculture. The capacity to cultivate crops in small spaces, rooftops, and even indoors makes hydroponics highly pertinent for modern living environments. Additionally, the use of different growing media and precise nutrient regulations (pH, EC, and ion concentration) plays a critical role in accomplishing maximum plant growth and yield. Overall, hydroponics represents a future-oriented agricultural technique that can assist considerably with sustainable food production, environmental conservation, and future food stability. Further research and cost-effective innovations are required to make this technology more convenient, especially for small-scale farmers.

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