Review Article

Recent trends for cultivation of crops by using Hydroponics

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Abstract

Hydroponics is recognized as one of the most advanced and adaptable approaches to crop cultivation, enabling plants to grow without soil through the efficient use of nutrient-enriched water solutions. This technology ensures optimal utilization of water, nutrients, and space, while allowing precise control over environmental parameters such as temperature, light, and pest incidence. Hydroponic farming is particularly valuable for food production in challenging ecosystems, including arid regions, mountainous areas, and extreme climatic zones. In addition to enhancing crop productivity, hydroponics improves produce quality, market value, and economic returns. The method also supports environmentally responsible agriculture by reducing chemical inputs, minimizing waste generation, and encouraging sustainable pest management practices. This review examines recent developments in hydroponic systems, types of cultivation methods, and the use of diverse soilless growing media, highlighting the advantages of hydroponics over conventional soil-based agriculture and its role in strengthening food security and resilient farming systems.

Keywords: Hydroponics, Methods, Cultures, Crops, Vegetable, Future.

Introduction

The rapid growth of the global population poses a major challenge to agricultural systems worldwide. According to FAO projections, the world population is expected to approach nine billion by 2050, necessitating an increase of more than 70% in global food production compared to 2007 levels (Anonymous, 2013). Simultaneously, urbanization is accelerating, with nearly three-quarters of the population projected to reside in metropolitan areas by mid-century (Singh et al., 2024). These trends, combined with climate change–induced stresses such as droughts, floods, rising temperatures, and pest outbreaks, have significantly affected crop productivity.

Degradation of natural resources, declining soil fertility, and limited availability of quality irrigation water have encouraged the adoption of alternative cultivation systems, particularly hydroponic vegetable production. For crops such as lettuce, herbs, and high-value vegetables that are often imported or sensitive to climatic variation, hydroponics offers a reliable and efficient production method (Anonymous, 2023). Consumption of fruits and vegetables is strongly associated with reduced risk of chronic diseases due to the presence of antioxidants, vitamins, and bioactive compounds such as beta-carotene (Block et al., 1992). Hydroponic cultivation allows manipulation of environmental factors, including nutrient supply, light intensity, and temperature, which can influence both yield and nutritional composition (Jan et al., 2020).

Comparative studies have demonstrated improved quality attributes in hydroponically grown crops, such as enhanced flavor, acidity balance, vitamin content, and carotenoid levels in lettuce and tomatoes (Anonymous, 2012). Moreover, hydroponic systems significantly reduce post-harvest waste; for example, nearly all hydroponically grown lettuce leaves are marketable and can fetch higher prices than conventionally produced counterparts (Bawiec et al., 2018). Improved nutritional quality and consumer acceptance further strengthen market opportunities for hydroponic produce (Mehra et al., 2017).

Hydroponics refers to the cultivation of plants in nutrient solutions without the use of soil. The term originates from the Greek words *hydro* (water) and *ponos* (labour) and was popularized by Dr. W.F. Gericke in 1936 to describe large-scale soilless crop production. While the concept of soilless cultivation has ancient roots, modern hydroponic systems were developed during the twentieth century to enhance food production in regions with limited land and water resources. In these systems, inert growing media such as sand, gravel, rockwool, coco-peat, and perlite provide physical support to plant roots while nutrients are supplied through water solutions (Maharana and Koul, 2011). Owing to its rapid global adoption, the hydroponics market has shown substantial growth, reflecting its increasing relevance in modern agriculture (Jan et al., 2020).

Historical Background of Hydroponics

The scientific understanding of plant nutrition has evolved over several centuries. Early contributions were made by Theophrastus (372–287 BC) and Dioscorides, whose botanical writings provided foundational insights into plant growth (Douglas and James, 1975). In 1627, Sir Francis Bacon documented early concepts of soilless plant cultivation in *Sylva Sylvarum*, which stimulated interest in water culture experiments.

Subsequently, John Woodward's experiments in 1699 demonstrated that plants grew more effectively in water containing dissolved minerals than in distilled water. During the nineteenth century, German scientists Julius von Sachs and Wilhelm Knop formulated nutrient solutions that enabled plants to complete their life cycles without soil, marking a major breakthrough in hydroponic research. These discoveries laid the groundwork for the development of modern hydroponic systems used today.

Scope of hydroponics/ controlled environment agriculture

Under protected cultivation, growing crops in hydroponics can be considered the most complex production system available today. In terms of farming systems, Ruthenberg (1980) classified hydroponic cultivation as a "high input – high output – high risk" system. In fact, the available techniques to date require considerable specialisation with sophisticated management and know-how as well as high financial inputs to realise expected production potential, otherwise the crop failures can be disastrous. Before going for a large-scale hydroponic system, the growers should be much more critical concerning site selection, structures, the growing system, pest control and markets(Yep, 2020).

Types of Hydroponic Systems

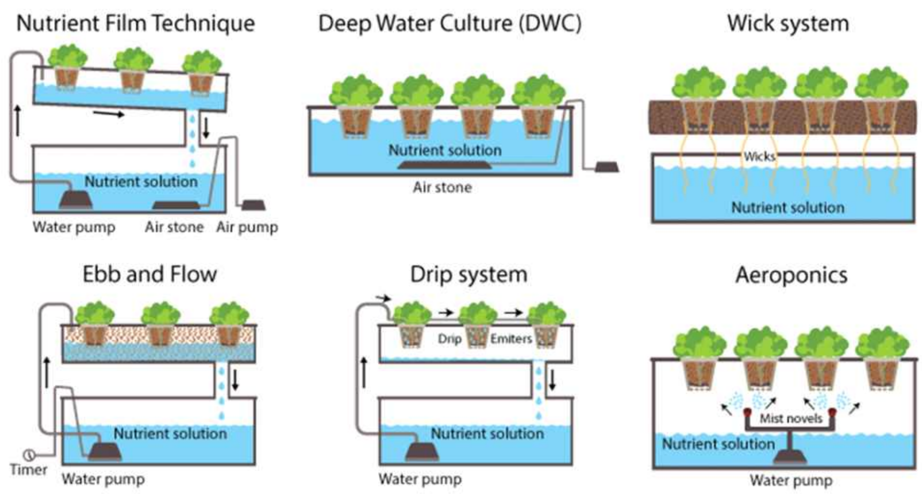

Fig. 1. Different types of hydroponics techniques

Water-based hydroponic systems are generally classified into three major approaches. One widely adopted method is the nutrient film technique **(NFT)**, in which plant roots are positioned within narrow channels or troughs, allowing a thin, continuously flowing layer of nutrient solution to pass over the root surface. This design ensures efficient nutrient uptake while maintaining adequate oxygen availability. NFT systems may operate as either open or closed circuits and have been reported to enhance lettuce yield by approximately 6–10%, making them particularly suitable for leafy vegetable production (Janick, 2003; Frasetya et al., 2021).

Another common water-culture method is the **raft or floating system**, where plants are anchored in lightweight support materials, such as polystyrene sheets, that float on an aerated nutrient solution. In this system, roots extend directly into the solution and remain continuously submerged. Raft systems typically function as closed systems and require regular monitoring and adjustment of nutrient composition to maintain optimal growth conditions (Janick, 2003).

Aeroponics represents a more advanced variation of water-based hydroponics, in which plant roots are suspended in the air rather than submerged in solution. Nutrients are supplied in the form of fine mist sprays, providing high oxygen availability and efficient nutrient absorption. Depending on system design, aeroponic setups may be operated as open or closed systems (Nir, 1982).

In contrast, medium-based hydroponic systems utilize inert substrates to support plant roots. The **ebb-and-flow system** involves periodic flooding of the growing medium with nutrient solution, followed by drainage back into a reservoir through gravity. This recirculating approach conserves nutrients and water, classifying it as a closed system (Sharma, 2018).

The **drip irrigation system** supplies nutrient solution directly to the root zone through emitters placed near individual plants grown in solid media. Variations of this system include vertical and tower-based designs, where plants are supported in upright structures filled with porous substrates. Nutrient solutions may be reused or discharged, depending on the system configuration (Naik, 2012; Sharma, 2018).

Finally, the **sub-irrigation system** relies on capillary action within porous growing media to transport nutrients from below the root zone, ensuring consistent moisture and nutrient availability without surface flooding.

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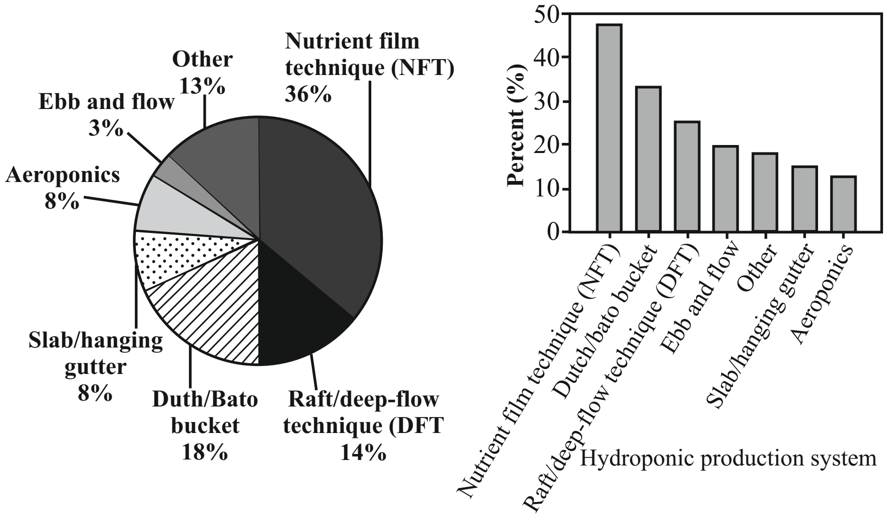

Fig. 1. The proportion of hydroponic production systems used by respondents of a 2017 U.S. hydroponic grower survey, based on space dedicated to each system (left), and the percentage of respondents using each type of production system based on frequency. (Sharma, 2018).

Growing Mediums in hydroponics

In hydroponic cultivation, various growing media are used to provide physical support to plant roots and to maintain an appropriate balance between moisture retention and oxygen availability. These media are generally inert, allowing nutrients to be supplied exclusively through the nutrient solution. One of the most widely used substrates is rockwool, a sterile and porous material produced by melting natural rocks such as granite or limestone at high temperatures and spinning the molten material into fine fibrous strands. These fibers are subsequently formed into cubes, slabs, sheets, or blocks suitable for plant growth. Rockwool has a high water-holding capacity; therefore, careful management is required to avoid oversaturation, which may restrict oxygen supply to roots and promote stem or root rot. Prior to use, rockwool is commonly conditioned by soaking in pH-adjusted water to stabilize its chemical properties (Treftz and Omaye, 2015).

Another popular medium is coco coir, derived from the outer husk of coconuts. Once regarded as an agricultural waste product, coco coir is now valued for its sustainability and favorable physical characteristics. Although it is organic in origin, coco coir decomposes slowly and contributes minimal nutrients, making it suitable for hydroponic systems. It is naturally pH neutral, exhibits high moisture retention, and provides good aeration for root development. Coco coir is commercially available as fine fibers or as coarser chips, with the primary difference being particle size (Mehra, 2017).

Perlite is an inorganic growing medium formed by heating volcanic minerals to extremely high temperatures, causing them to expand and form lightweight, porous particles. It has a neutral pH, excellent drainage capacity, and strong capillary action, which supports effective water movement within the root zone. Perlite can be used alone or blended with other substrates; however, due to its low density and tendency to float, it may be less suitable as a standalone medium in certain flood-and-drain systems (Naik, 2013).

Vermiculite, a heat-expanded silicate mineral, shares several characteristics with perlite but has a higher capacity to retain nutrients due to its elevated cation exchange properties. Like perlite, vermiculite is lightweight and may float in hydroponic systems, but it is particularly useful where nutrient retention is desired.

Oasis cubes, commonly used in horticulture, resemble rigid floral foam and function as open-cell substrates capable of absorbing both water and air. While their properties are similar to those of rockwool, oasis cubes are less prone to becoming waterlogged. Nonetheless, prolonged contact with standing water should be avoided to prevent root suffocation (Maitra et al., 2020).

Sand is another frequently used hydroponic medium, characterized by small particle size and moderate water retention. Due to slower drainage compared to coarser substrates, sand is often mixed with materials such as perlite, vermiculite, or coco coir to enhance aeration and moisture balance around the roots.

Rice hulls, an agricultural by-product of rice milling, may also be utilized depending on availability. Although organic in nature, rice hulls decompose slowly, similar to coco coir, making them suitable for hydroponic applications (Lakshmanan et al., 2020). Among the different forms, parboiled rice hulls are preferred, as the steaming and drying process eliminates contaminants such as weed seeds, fungi, and bacteria, resulting in a clean and sterile growing medium (Chavan and Kadam, 1989).

Nutritional quality of hydroponically grown produce

At present, there is no definitive agreement regarding whether hydroponically produced crops are nutritionally superior to those cultivated in soil. However, the precise regulation of environmental factors such as nutrient supply, water availability, light intensity, and temperature in hydroponic systems offers significant potential for improving the nutritional composition of horticultural produce. Consequently, it has been suggested that hydroponically grown crops may, under optimized conditions, attain equal or enhanced nutritional value compared to conventionally grown crops (Berman et al., 2016).

Comparative studies conducted at the University of Nevada, Reno demonstrated that strawberries and raspberries cultivated using hydroponic techniques contained notably higher concentrations of vitamin C, vitamin E, and total polyphenols than their soil-grown counterparts. In contrast, hydroponically produced strawberries exhibited reduced levels of fructose and glucose, indicating possible benefits for consumers seeking lower sugar intake (Naik, 2013).

The nutritional significance of tomatoes is largely attributed to their rich phytonutrient profile, which has been associated with protective effects against cardiovascular disorders (Willcox et al., 2003). More broadly, numerous studies have established a strong relationship between increased consumption of fruits and vegetables and reduced cancer risk, primarily due to the presence of antioxidant compounds that neutralize harmful oxygen radicals and limit cellular damage (Wargovich, 2000; Block et al., 1992; Hennekens, 1994).

Similarly, hydroponically grown raspberries have been reported to contain significantly lower concentrations of fructose and sucrose when compared with soil-grown plants, suggesting an additional nutritional advantage. Such findings highlight the potential of hydroponic cultivation to provide nutritionally optimized produce, particularly in urban and water-limited environments. Nevertheless, further research is required to identify ideal production practices and to fully evaluate long-term nutritional outcomes for hydroponically grown berries (Choudhary et al., 2021).

Table 1. Various species of plants grown under soil less hydroponic system.

Type of crops	Name of the crops
Cereals	Rice, Maize
Fruits	Strawberry
Vegetables	Tomato, Chilli, Brinjal, Green bean, Beet, Winged bean, Bell pepper, Cucumbers,Melons, green Onion
Leafy vegetables	Lettuce, Spinach, Celery, Swiss chard, Atriplex
Condiments	Coriander leaves, Methi, Parsley, Mint, Sweet basil, Oregano
Flower / Ornamental crops	Marigold, Roses, Carnations, Chrysanthemum
Medicinal crops	Indian Aloe, Coleus
Fodder crops	Sorghum, Alfa alfa, Bermuda grass, Carpet grass

(Singh and Singh, 2012; Das *et al.*, 2012; Hayden, 2006).

Table 2: Vegetable production under hydroponics in India.

Vegetables	Production (g/sqm/ day)
Carrot	56.5
Cucumber	226
Garlic	57
Ginger	57
Leek	57
Green bean	113
Lettuce	226
Onion	56.5
Pea	113
Potato	56.5
Salad greens	226
Tomato	113

(Singh and Singh, 2012; Das *et al.*, 2012; Hayden, 2006).

Table 3: Crops which can be grown on soil-less culture are given below.

Type of crops	Name of the crops
Vegetables	*Brassica oleracea var. botrytis* (Cauliflower), *Cucumis sativus* (Cucumbers), *Lycopersicon esculentum* (Tomato), *Capsicum frutescens* (Chilli), *Solanum melongena* (Brinjal), *Phaseolus vulgaris* (Green bean), *Beta vulgaris* (Beet), *Psophocarpus tetragonolobus* (Winged bean), *Capsicum annum* (Bell pepper), *Brassica oleracea var. capitata* (Cabbage), *Cucumis melo* (Melons), *Allium cepa* (Onion), *Raphanus sativus* (Radish).
Leafy vegetables	*Ipomoea aquatica* (Kang Kong), *Lactuca sativa* (Lettuce).
Cereals	*Oryza sativa* (Rice), *Zea mays* (Maize)
Fruits	*Fragaria ananassa* (Strawberry)
Flower/ Ornamental crops	*Tagetes patula* (Marigold), *Rosa berberifolia* (Roses), *Dianthus caryophyllus* (Carnations), *Chrysanthemum indicum* (Chrysanthemum)
Condiments	*Petroselinum crispum* (Parsley), *Mentha spicata* (Mint), *Ocimum basilicum* (Sweet basil), *Origanum vulgare* (Oregano)
Fodder crops	*Sorghum bicolor* (Sorghum), *Medicago sativa* (Alfalfa), *Hordeum vulgare* (Barley), *Cynodon dactylon* (Bermuda grass), *Axonopus compressus* (Carpet grass).
Medicinal crops	*Aloe vera* (Indian Aloe), *Solenostemon scutellarioides*

(Singh and Singh, 2012; Das *et al*., 2012; Hayden, 2006)

Table 4: Yield comparison of some vegetables between soil and hydroponic system

Crop	Soil (avg per acre)	Hydroponics (avg per acre)
Lettuce	9-10 tons	300-400 tons
Strawberries	20-25 tons	50 tons
Cucumber	15-20 tons	200 tons
Tomato	10-12 tons	180-200 tons
Bell pepper	10-12 tons	120-140 tons
Potato	8-10 tons	60-70 tons
Cabbage	6-7 tons	10-12 tons

(Lateef *et al*., 2018).

Recent advancements in hydroponics

Hydroponics is increasingly regarded as a promising cultivation approach for future agricultural production, particularly for high-value crops such as tomatoes, lettuce, and other leafy vegetables. Greenhouse-based hydroponic systems are widely adopted in regions across Europe and the Asia–Pacific due to their ability to produce uniform, high-quality yields. Besides tomatoes and peppers, several other crops, including cucumbers, cucurbits, and cantaloupes, have been successfully cultivated using hydroponic techniques (Sharma et al., 2018).

Rapid urban expansion, population growth, and the rising popularity of community-supported agriculture initiatives have contributed significantly to the global expansion of hydroponic farming. These factors have strengthened local food supply chains and accelerated the development of commercial hydroponic enterprises worldwide (Gilmour et al., 2019). In response to shrinking arable land and increasing food demand, hydroponics and aeroponics are emerging as viable alternatives to conventional agriculture (Sardare and Admane, 2013).

Experimental studies have demonstrated that hydroponic cultivation does not adversely affect plant morphology. For instance, Lei et al. (2021) reported no significant morphological differences between hydroponically grown lettuce and conventionally cultivated plants. However, long-term reuse of hydroponic media may negatively influence crop productivity. Talukder et al. (2018) observed reduced strawberry yields when growing media were reused for extended periods, although treatment of the media using direct current electro-decontamination (DC-ED) and alternating current electro-decontamination (AC-ED) effectively restored plant growth.

Pest management remains a critical challenge in hydroponic systems, particularly in greenhouse environments. Tetranychus urticae has been identified as a major pest affecting hydroponically grown cucumbers, and integrated pest management (IPM) strategies have been recommended as an effective control approach (Saleem et al., 2019). Advances in controlled environment technologies have further improved crop performance; Gao et al. (2020) demonstrated that specific red-to-blue light ratios in LED systems significantly influence growth and nutrient accumulation in hydroponically grown spinach. Additionally, nutrient solution pH plays a crucial role in plant health, as extreme pH levels (5, 8, and 9) have been shown to adversely affect plant growth, whereas near-neutral conditions support optimal development (Hopkinson et al., 2019).

Overall, the expanding adoption of hydroponic systems has enhanced crop production efficiency while reducing labor requirements and environmental impact, highlighting the sustainability potential of this technology.

Future scope of hydroponics in India

Although a large proportion of Indian farmers reside in rural areas and remain unfamiliar with hydroponic technology, the future potential of this cultivation method in India is considerable. Rapid urban expansion and increasing pressure on freshwater resources, particularly in major metropolitan regions, have intensified the need for water-efficient agricultural practices. Since conventional agriculture accounts for the majority of freshwater consumption, a transition toward hydroponic systems could result in water savings exceeding 80%, thereby easing competition between agricultural and domestic water demands.

Food safety concerns further strengthen the relevance of hydroponics in India. A significant portion of conventionally grown vegetables contains pesticide residues that pose risks to human health. In contrast, hydroponic cultivation offers an effective pathway for producing cleaner and safer food with minimal chemical inputs. The adaptability of hydroponic systems has already been demonstrated across diverse environments, and future applications may include the use of desalinated seawater in drought-prone coastal and arid regions, expanding food production capacity in areas previously unsuitable for agriculture.

Hydroponics represents an innovative scientific approach capable of enhancing productivity across food, fodder, and ornamental crops while maintaining high quality standards (Putra and Yuliando, 2015). The technology is particularly suited to densely populated regions, where it enables efficient production of local vegetables and flowers within limited space. With continued technological advancement and system modernization, hydroponic cultivation could support year-round crop production across a wide range of climatic zones.

On a global scale, hydroponics has demonstrated its ability to address food security challenges in regions facing constraints related to land and water availability. The technology has the potential to supply nutritious food to large populations in Asia and Africa, offering a sustainable solution for long-term crop management and food production (Maharana and Koul, 2011). Several countries have already integrated hydroponics into mainstream agriculture; for example, Japan has explored hydroponic rice production to meet domestic food requirements (De Kreij et al., 1999), while Israel has successfully utilized hydroponics to cultivate berries, citrus fruits, and bananas under arid climatic conditions (Van Os, 2002).

Beyond conventional agriculture, hydroponics is increasingly recognized as a versatile production system capable of functioning in extreme environments, including mountainous regions, deserts, and even controlled habitats such as space stations. The growing global demand for hydroponic cultivation reflects its adaptability and sustainability in both developing and developed nations (Trejo-Téllez and Gómez-Merino, 2012).

Future research priorities should focus on evaluating seed varieties for biomass yield and nutrient composition, conducting long-term feeding trials of hydroponically produced fodder across different livestock categories, and developing region-specific feeding strategies tailored to diverse agro-climatic conditions (Barman et al., 2016).

Conclusion

Hydroponic farming has gained considerable attention in recent years due to its capacity to produce high-quality crops using resource-efficient methods. This cultivation approach is particularly advantageous in regions experiencing water scarcity, as hydroponic systems allow for the recycling and efficient utilization of water. Crops grown under hydroponic conditions often exhibit enhanced nutrient content and are produced with minimal exposure to harmful contaminants, making them suitable for health-conscious consumers.

As one of the most intensive forms of modern crop production, hydroponics is increasingly adopted in both developed and developing countries where land availability is limited. The system is characterized by high productivity, reduced water consumption, and lower environmental impact compared to conventional soil-based agriculture. By supplying plants with a continuous and readily available source of nutrients, hydroponic cultivation enables faster growth rates—often up to 50% quicker than traditional methods—while also achieving substantially higher yields.

The rapid expansion of hydroponic practices has stimulated extensive experimentation and innovation, particularly in indoor and protected cultivation systems. Continued research and technological development in this field are expected to further enhance the efficiency, scalability, and sustainability of hydroponic farming, reinforcing its role as a viable solution for future food production challenges.

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