Defence Life Science Journal, Vol. 8, No. 2, April 2023, pp. 162-169, DOI : 10.14429/dlsj.8.18024

Recent Advances in Hydroponic Culture Media: Composition and Their Effect on Plant Growth

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ABSTRACT

The growing demand for food resources is facing a shortage of supplies subject to the reduction in cultivable land globally, and a dire need for alternative cultivation strategies is the need of the hour.Scientists and researchers throughout the world are focusing onalternative cultivation strategies. However, this kind of cultivation is scarce in developing countries, including India, where the impact is paramount and will woo offthe growing population and reduce cultivable land, as per land census data (2020).Hydroponics isa robust solution forgrowing plants under controlled and regulated cultivation conditions.The term hydroponics means the water at work, which primarily focuses on giving specific nutrientsto support the growth and development of the plant.This opens floodgates for researchers to formulate and optimize novel nutrient growth media.Agricultural output has been duly enhanced with this multifaceted intensive technique.Marketing research data projects that thehydroponics market will be 12,000 million US dollars by 2025.The nutrient solutions are designed to provide all essential macro and micronutrients to plants.The well-aerated media with essential nutrients, crucial organic salts, and balance of ionic concentration, conductivity, and pH, is vitalfor hydroponic culture, a solution to redundant environmental concerns.The current review highlights recent advances in the optimization of hydroponic media compositions.The synergistic effects of a multitude of media on plant growth and product yield have been discussed.

Keywords: Soilless cultivation; Nutrient media; Hydroponics optimisation studies; pH; Electrical conductivity; Media designing

1. INTRODUCTION

Industrialisation and globalisation have provided an impetus to the global economy,with scientific interventions translated into the technological know-how of providing euthenics support to mankind.The growing human population has increased the burden on the cultivable land for more and more production of agricultural products. Land use as a resource is not limited to food production, but much such agrarian produce on the ecosystem for improving the productivity of food products is reducing cultivable land throughout the world.Even in developing countries, including India, the impact is paramount and will result in worsereduced cultivable land. The agricultural census data of India showed reducing in the yield of food grains with the passing years, necessitating the need to explore alternative cultivation strategies (Ministry of Agriculture, Government of India, 2020). Figs 1 (a) & (b) show the cultivable land (million hectares) and the yield of the crop in Indiafrom 1950 to 2020.[1] The data in Fig 1(a) showed insignificant change in the area under cultivation from 1970 till 2020 with a concomitant increase in the yield of crop cultivated (Fig.1(b)), indicating the use of better techniques, cultivars, germplasms, and a possible burden on the available land for high productivity, to meet the growing population demand.[1]

Hydroponic (or soil-less culture) is one such system that is well adapted to grow various plants for a sustained and hyper yield of products.[2] It is the art and science of growing plants without soil and with or without any artificial support or media.[3,4] The word was coined from the Greek words *hydro* and *ponos,* meaning “water working”.[4] The technique holds its name where the solution of organic and inorganic salts or fertilizers is provided to plants using a key in water under different setups and conditions. The technique has increased crop production in a multifold. The system incorporates aqueous solutions supplemented with nutrients and salts for plant cultivation.[5] The other media components could be Rockwooland perlite, and the system can continuously provide them open and closed.[5] As a result, the hydroponic cultivation system provides higher crop productivity and economic competitiveness.[5] The determining factor

Received : 11 April 2022, Revised : 02 February 2023
Accepted : 07 February 2023, Online published : 07 June 2023

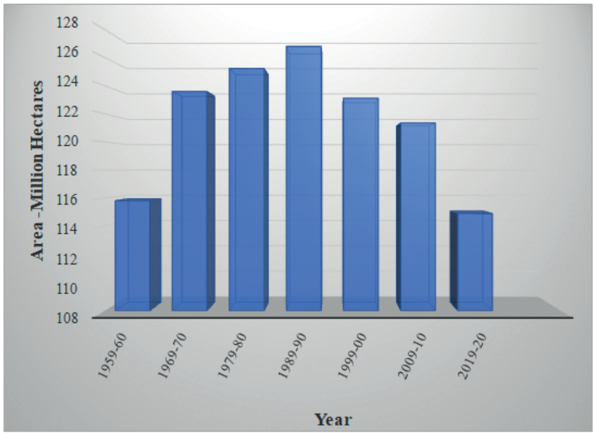

Figure 1(a). Area under cultivation in India (1950-2020 data), based on Agriculture statistics at a glance2020, Ministry of Agriculture and Farmers Welfare, Government of India.

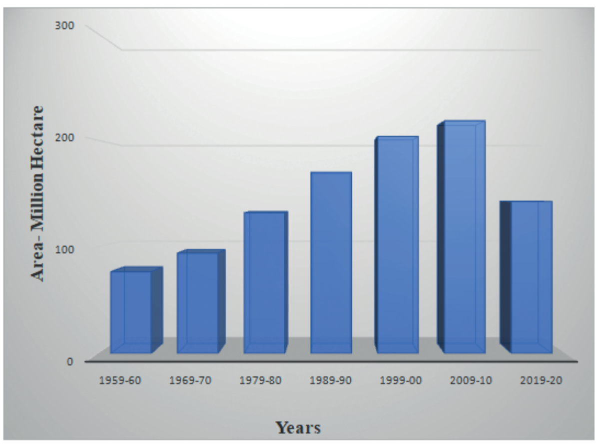

Figure 1(b). Increase in production of crops in India, from agriculture harvest (1950 - 2020 data), based on Agriculture statistics at a glance, 2020, Ministry of Agriculture and Farmers Welfare, Government of India.

which makes this system efficient is the availability of nutrients in the hydroponic solutions. This highlights the importance of nutrient solutions in Hydroponics. The nutrient solutions are designed to provide all essential macro and micronutrients to plants. These nutrient solutions differ in their ratios of salts and ions present and available for plant growth based on different plant growth characteristics. The continuously flowing nutrient solution in a soilless culture is essential for improved growth and better aeration in the system.[3]

2. JOURNEY OF HYDROPONICS FROM ANCIENT TO RECENT COMMERCIAL INITIATIVES

It is not startling to know that Roman Empire had hanging gardens, which were developed as aesthetics, on rooftops, quoted by Halley,1965.[6-9] Likewise, Resh[10] highlighted the floating gardens of the Aztecs Chinese, anchored to lake bottoms or trees, famously accounted for by Marco Polo in his 13th century expeditions, on account of the marshy areas and food cultivation. In 1699, end of the 17th century, John Woodward discovered that minerals dissolved in water contributed to plant growth and development rather than water[10] (Resh 1989).[6-9] As discussed in the previous paragraph, the critical nomenclature W.F Gericke who coined the term Hydroponics 1930), posed the water dynamics as an essential scientific inclusion upon which this art is formulated makes a strong case for modern botanists and academicians. The significant technological advancements in state of the art are: Nutrient Film technique, Aeroponics, Flood and drain techniques, Tube culture. These techniques are based on system categorisation (open or closed), system design, nutrient supply, and management.

In the 19th century, chemical scientists made solid cases for defining the chemical makeup of plants and their requirements, chiefly discussed by De Saussure and Boussingault. Plants need nutrients to feed their metabolic pathways. This was understood by Sachs and Knops (1860-61), and they developed mariculture. Arnon, Hoagland, Shive, Tollens, Tottingham, and Trelease joined the league. Gericke conducted various lab experiments from 1925-1935 with tomatoes, beets, radishes, carrots, cereal crops, fruits, and flowers. It is fascinating to note military food requirements during world war II that were met in Japan by hydroponics amounting to more than twenty hectares of hydroponic plant and about 3,180,000 pounds.[6-9]

In the subsequent half of the 20th century the commercial advantages of this cultivation were spread to Italy, Spain, France, England, German, Sweden, USSR, and Israel.With the advent of plastics, the cost of plant setupsdecreased, as tanks now reduced construction costs with concrete.With the inclusion of pumps, timers added, other additional tails, and plastic plumbing parts,the operational cost was reduced favorably. The countries like Mexico and the Middle East benefitted from water conservation methods of plant cultivation.[6-9] In this 21st Century, Israel is a leading producer of hydroponics crops. Though the journey has traversed a tremendous 60-year period globally, it is still exciting and opens new avenues of research in nutrient management and new formulations of nutrient potions for plants, even entering medicinal crops.The current insights and commercial initiatives are clubbed in the subsequent paragraph in detail.

2.1 Market Trend of Hydroponics

According to the global market research report[10], the global hydroponic market (primarily for fruits and vegetableshas seen a compounded annual growth rate of around 6.5 % and is expected to be a market worth approximately 12,000 million US dollars by 2025. According to the report published by Tech Sci Research[11], Europe and the Asia Pacific account for about 45 % of the market share of HydroponicsReport from Market Data Forecast[12] forecasted the aquaponics market in Asia pacific to increase at a CAGR of 13 % by 2023. The technology of the beings drives the Indian segmentation in the hydroponics market; nutrient film technique, drip system, ebb & flow/ flood & drain system, others, also by the location of hydroponic setups; to name a few -outdoor farming, indoor farming specified for fruits and vegetables namely tomato, strawberry, bell pepper, leafy vegetables, cucumber, others, flowers.The states actively pursuing Hydroponics are Andhra Pradesh, Telangana, Gujarat, Haryana, Maharashtra, and others, as per Data Intelligence Research Report, 2019.[14]

Based on the available reports, there are forty-plus commercially active hydroponic farms in India, and a couple of farms are underway.[9] Without cold chain logistics, farms" produce being perishable ends up getting consumed in the nearby cities. In India, these farms predominantly grow green leafy vegetables and herbs viz lettuce, Italian basil, cherry tomatoes, cucumbers, and red and yellow bell peppers. Ranking in volume and value puts giant green vegetables ahead of leafy greens.The startups which created the Hydroponics market and now have a sizeable market share include- Letectra Agritech Private Limited, DS Group, Neoterra Farming Technologies Private Limited, Sparsh Bio Life, Delhiponics, Hydroherbs, Simply Fresh Inc, Junga Freshngreen Pvt Ltd, Triton Food Works Pvt Ltd., and Fresco.[13]

3. HYDROPONIC CULTURE MEDIA

3.1 Composition and Effect

The success of hydroponic cultivation relies on the composition of the medium or solution used for cultivation and operational conditions.The well-aerated water with essential nutrients, inorganic salts, and a balance of ionic concentration, conductivity, and pH, is a vital component of hydroponic culture.The nutrient solution, when in contact with the roots of the plant, provides the required nutrient components, which are absorbed by the roots via osmosis and assist in plant growth and metabolism. Thus an optimum media composition must be designed to improve plant growth and metabolism.

As far as media composition is concerned, scientific studies are focusing more and more on developing an optimum solution for the growth of the plant and its metabolism.Without any gold standard, every study exploring media composition is unique as it paved the way for developing robust media composition for plant growth. Studies by nutrient compared the effect of different media compositions of varying salt compositions and conductivities on the development of *Arabidopsis thaliana.*[14]

Hydroponic systems provide nutrients in the form of ions which are inorganic salts essential for plants, also, these systems sometimes contain organic iron chelates.[15-17]

Previous studies have shown that the major ions that are provided to the plant through hydroponic cultivations include hydrogen, nitrogen (reported for its assimilation and nutrient signaling processes)[18], phosphorus, potassium, calcium, magnesium, sulfur, iron, copper, zinc, manganese, molybdenum, boron, chlorine and nickel due to their versatile role in plant growth and metabolism as shown in Table 1.[2,19,20] The unique arrangement of hydroponic cultivation is that the surrounding environment meets the carbon (C) requirement.Commercial nutrient solutions provide plants with macro- and micronutrients, elicitors, and growth enhancers.[21] In addition, Trejo-Téllez[22], *et al.*also reported the ionic balancing and the availability of nutrients (macro- and micronutrients present as ions) to plants, thereby retarding the concentration linked toxicity (due to salts) in plants. The parameter is significant and needs exploration with different plant systems. Nowadays, markets are flooded with a plethora of nutrient mixes based on Hoagland Anderson's (1950) recipe.

3.1.1 Salts and Ions of Hydroponic Media

The uptake of nutrients by plants is a continuous process.Experiments by Hoagland and team (1940-43) demonstrated the relationship between nutrients absorbed and changes in ionic balance. Previous studies have reported the presence of Nitrogen (N), Phosphorus (P), Sulphur (S), Potassium (K), Calcium (Ca), and Magnesium (Mg) as significant elements.Steiner proposed the composite ratio of anions and cations in media to explore the association between pH and ionic availability for plant update.[23-25]

A previous study by Siddiqi, *et al.* highlighted the availability of nutrients in the cultivation of tomatoes, where the yield was not affected with a 50 % reduction in nutrient availability keeping other factors intact. Kang & van Iersel[26] explained the increase of 2X concentration of Hoagland's media in early flowering in the Salvia splendens plant.

In another study, Fanasca[27], *et al.* described potassium ions in excess increased lycopene concentration in SolanumLycopersicum (tomato). These explanations were well assessed by Juárez,[28] concluding that the requirement of nutrients depends on the plant's genus, the system of cultivation available, the different recipes for nutrient solutions, and the environment.The media composition vis-à-vis their association with growth, morphogenesis, and metabolism are shown in Table 2(a,b).[19]

The optimisation of nutrient solutions is a vital step based on plant requirements (age of plant and species), type of cultivation system, and other abiotic factors.[29] Thus, nutrient solutions are formulated based on plant requirements. The plants in early growth stages require more macro-elements for structural growth, e.g., phosphorus for root growth, compared to the fruiting stage, where more potassium is needed. Other abiotic factors, like temperature and light intensity, are well adjusted to maintain the growth requirement and photoperiod of the plant.

Keith & Roberts 2003 explained the role of salt and their strength on vegetative growth, fruiting and flowering concerns while designing a nutrient solution. In a recent study by Aggarwal and Mathur (2020), a unique representation of the growth of *Bacopamonnieri*, a medicinal herb of high commercial value, was cultivated in a commercial hydroponic media and showed higher biomass and similar saponin yield, giving a cost-effective alternative for tissue

Table 1. Role of essential elements in the growth of the plant

Macro-Nutrients	
Carbon (C)	An integral part of cell walls, sugars, chlorophyll, 50 % plant dry weight
Hydrogen (H)	Maintaining ion balance, turgor pressure
Oxygen (O)	Sugars, starch, cellulose, respiration
Nitrogen (N)	Amino acids, Coenzyme, chlorophyll Deficiency- small, spindly plants Toxicity- vigorous growth, delayed fruit ripening, susceptibility to pests
Phosphorus (P)	Sugars, phosphates, ATP, flowering, fruiting, root growth Deficiency- stunted growth, discolouration of leaves, curling Toxicity- redundant availability of copper and zinc
Potassium (K)	Protein synthesis, root hardness, sugar, starch formation Deficiency- mottling of leaves, fungal infestation Toxicity- secondary magnesium deficiency
Micro-Nutrients	
Calcium (Ca)	Cell wall formation Deficiency- stunting, crinkling; Blossom end rot-BER in tomatoes Toxicity-can't be easily identified
Sulfur (S)	Proteins, water uptake, a natural fungicide, seeding, fruiting Deficiency- yellowing of leaves, uncommon Toxicity- growth retardation
Iron (Fe)	Chlorophyll formation (Iron chelator), growth processes, respiration of sugars Deficiency- early fall of blossoms, faint colouration, yellowing of veins, death around leaf margins Toxicity- rare and unidentified
Magnesium (Mg)	Chlorophyll and enzyme production Deficiency- older leaves curl, yellowing of leaf veins Toxicity- rare, unidentified
Boron (B)	Cell wall formation with calcium Deficiency- Brittle stems, poor growth Toxicity- yellowing of leaf tip and death
Manganese (Mn)	Biocatalysts in the growth process, formation of oxygen during photosynthesis Deficiency- yellowing of leaves, non-flowering Toxicity- less availability of Fe
Molybdenum (Mb)	Metabolism of Nitrogen, Nitrogen fixation Deficiency- small, yellow leaves Toxicity- bright yellowing of tomato leaves
Zinc (Zn)	Chlorophyll production, nitrogen metabolism, respiration Deficiency- small and crinkled leaves Toxicity- reduce the availability of Fe
Copper (Cu)	Enzyme Activation, respiration, photosynthesis Deficiency- pale and yellow spotted leaves Toxicity- reduce the availability of Fe
Cobalt (Co)	Trace amounts needed by legumes while Nitrogen fixation, an area of research for scientists

culture.In another study by Shete[29], *et al.* (2017), the cultivation of Mentha arvensis (Mint) plants in aquaponics was studied for biomass and phytocompounds.[30] In another study by Delden 2019, on Arabidopsis thaliana effects of different media were compared with Moorashige and Skoog solution.[31] Results revealed better results in Conn, Tocquin, and ½ Hoagland media.

On the contrary, Moorashige and Skoog's media resulted in growth retardation and stressed plants. Another recent report by Kolega[31], *et al.* on *Ocimumbasilicum L.* (Basil), for its nutraceutical profile in different growth media and their effect.[32] The solutions were fortified with sulphates and phosphates for the developmental concerns of the plants. The experiments showed an increasing trend of biomass growth in sweet basil with increasing nutrient supply (Nitrogen and Sulphur availability), and the resultant metabolomics profile showed modulation in about 400 secondary metabolites, supporting the previous

Table 2(a). Composition for 1 gallon of Nutrient solution for inducing vegetative growth, fruiting, and flowering in Plants: (Adapted from Keith and Roberts, 2003)

Components	Concentration (g)		
	Vegetative growth	Fruiting	Flowering
Calcium Nitrate $Ca(NO_2)_3$	6	8	4.10
Potassium Nitrate KNO_3	2.09	2.80	2.80
Potassium Sulphate K_2SO_4	0.46	1.70	06
Mono-potassium Phosphate KH_2PO_4	1.39	1.39	1.39
Magnesium Sulphate gSO_4*7H_2O	2.42	2.40	2.40
7 % Fe chelated trace elements[#]	0.40	0.40	0.40

Table 2(b). Composition of trace elements: (Adapted from Keith and Roberts, 2003)

Trace element	Percentage
Iron (Fe)	7 %
Manganese (Mn)	2 %
Copper (Cu)	0.10 %
Zinc (Zn)	0.40 %
Molybdenum (Mb)	0.06 %
Boron (B)	1.30 %

studies.[33,34,36] The medicinal herbs are well-researched for their secondary metabolites. The reports have well established that elements like nitrogen are significant for carbon metabolism and, as a precursor for secondary metabolic pathways,have demonstrated the relevance of genotype in the modulation of phenolics production.[37,38] Other herbs like chicory are being researched in different nutrient solutions for their robustness while cultivated.[38]

Some medicinal herbs like Cichorium, Withania, and Echinacea have been produced using an aeroponic system with a specified nutrient solution with profound growth results.[39] Another deep study in the rugged terrain of India up in the Himalayas was strenuously studied was conducted under the aegis of the Defence Institute of Bio Energy Resource, Haldwani, on how rainwater harvesting and soil less culturing of vegetables can promise food for all sustainably.[40]

Recent research on developing high-quality tomatoes using Hydroponicsighlighted that nutritional resources, like ammoniacal nitrogen, affected the taste of tomatoes negatively when tested with different compositions of media.[41] Another study with Tetragoniadecumbens Mill shows how the chlorophyll content, growth characteristics, and nutrient uptake are affected by different fertigation levels in hydroponics conditions.[42] The statement holds much-valued importance that hydroponic systems with optimum nutrient solutions for planting in higher densities give a robust cultivation system compared to cultivation in soil.

3.2 Conductivity and pH of Hydroponic Media

The media's Electrical Conductivity (EC) is based on its composition, which is reflected similarly in its Osmotic Potential (OP). The existing alkalinity of the solution (often associated with the pH of the solution) affects the availability of macro- and micronutrients, including cations and anions in the solution.Studies have reported a high impact of the gradation of pH change on plant growth.[43] Some studies have researched the effect of pH and associated nutrients available to the plant in the hydroponic media.[17] In a study on *Triticum, aestivum* manganese precipitated on root surfaces based on pH.[44] In a highly acidic environment, the salts of Fe^{2+}, Mn^{2+}, PO^{3-4}, Ca^{2+}, and Mg^{2+} are insoluble, affecting plants' uptake.[21] Most pH-dependent studies on different plants have been performed in a range-bound manner (5.5-6.5) of soil used for cultivation. Roosta and Rezae (2014) reported the role of the pH of Hoagland's media (half strength) on the growth of the rose plant.[45] The effect was analysed by observing plant weight (both fresh and dry), the number of flower buds, and the second thickness of the plant estimated as stem diameter.

Results have shown a positive impact on plant growth with increasing pH from 4.5 to 6.5. However, the increase from the range mentioned earlier in pH negatively affects the plant'sgrowth and other morphological features.

Another essential property of hydroponic media, often associated with pH and salt composition, is the press's Electrical Conductivity (EC). It measures the number of ions present in the plants and Osmotic Pressure (OP), indicative of the water potential.[46,47] Based on the previous report, it can be proposed that EC between 1.5 - 2.5 ds m^{-1} and higher EC means higher OP, while lower EC plant health is jeopardised.[48] The previous study has shown higher availability of ions of sodium, potassium, magnesium, and calcium in Deep Sea Water (DSW).[48] The state of art research report about the role of temperature in the uptake of oxygen and solubility of ions in the solutions based on different plant systems.

The recent advances provide insight into current development on the role of hydroponic culture media composition (including pH and conductivity) on the responses of plants. The review provides an impetus for the scientific community to explore further the role of hydroponic media in enhancing plant growth and metabolite yield from less explored, commercially important medicinal plants.

4. CONCLUSION

The growing global cues to accept hydroponicsas a suitable alternative to cultivation with intentional improvement in plant biomass yield, derived product, and faster growth, provided a scientific impetus to explore the role of cultivation conditions on plant growth. Hydroponic media play a pivotal role in hydroponic cultivation. Hydroponic culture exhibits itself as a versatile technological advancement where optimum control of pH and other determining factors paved the way for developing enhanced production systems. It is cost competitive compared to field cultivation.

The existing studies have shown the importance of temperature, EC, OP, and abiotic parameters in the uptake of nutrients. Based on existing studies and results, it may be concluded that the availability of various inorganic salts in a limited concentration range under defined operational parameters plays a pivotal role in different developmental stages of plant growth. The optimisation of nutrient compositions and their synergistic effect in association with abiotic conditions need to be explored to develop a robust solution to the differing demand for nutrients and salts among different plant systems. The technique also obtrudes as a sustainable solution to global food scarcity. The shreds of evidence in the review clearly state the need for developing a consistent approach toward media design.Researchers with state-of-the-art techniques can thus develop a straight forward process based on studies, answering practical economic realities of advanced hydroponic setups.[49-52]

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