Agr. Nat. Resour. 58 (2024) 785–800

AGRICULTURE AND NATURAL RESOURCES

Journal homepage: http://anres.kasetsart.org

Review article

Navigating the research landscape of hydroponics: Past developments and future trajectory

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Article Info

Article history:
Received 7 March 2024
Revised 23 July 2024
Accepted 26 July 2024
Available online 31 December 2024

Keywords:
Food security,
Food-water-energy nexus,
Hydroponics,
Research trends,
Sustainability

Abstract

Importance of the work: The rising global food demand threatens conventional farming's sustainability due to limited natural resources, making hydroponics a potentially vital solution. However, to date, no scientometric study has examined the impact of hydroponics on water and energy resources for sustainable food production, nor has there been any analysis of the progress of hydroponics regarding sustainable farming practices.

Objectives: To understand the technological development in hydroponics over recent years and its potential in achieving food security in the light of sustainability and to envision the advancements required to overcome current limitations for its application in sustainable farming.

Materials and Methods: Scientometric analysis was undertaken based on hydroponic technology literature from 2011 to 2021, gathered from Scopus and Web of Science. In total, 2,447 unique articles were obtained. The data were visualized and interpreted using the CiteSpace 5.8 R3 software, applying cluster analysis techniques, with nodes consisting of "countries", "keywords", and "articles".

Results: Over the study period, hydroponic technology has consistently grown, with an average positive relative growth rate of 0.315 and a mean doubling time of 2.560 yr, indicating constant growth in the field. Agriculture and Environmental Science, and Ecology have been the most researched fields, comprising roughly 17% and 10%, respectively, of total publications with major contributions from the USA, China and Brazil. During the study period, hydroponics research has emphasized yield enhancement, system automation, nutrient management and bio-fortification. Even though hydroponics has good prospects as an adjunct to conventional agricultural systems for attaining global food security, its progress has been constrained at the present level of development by four key issues: 1) high energy consumption; 2) incomplete nutrient utilization; 3) concern for food safety (when integrated with water reclamation); and 4) high initial investment.

Main finding: Hydroponics, as an adjunct to conventional agriculture, has good prospects to assist in achieving global food security. System sustainability should be achieved through future research focusing on: 1) nutrient uptake maximization; 2) integration of wastewater treatment with hydroponics, while achieving water reclamation and food safety; and 3) optimization of power requirements.

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https://doi.org/10.34044/j.anres.2024.58.6.12

Introduction

The world population is growing and is now in excess of 7.8 billion (Thoradeniya and Jayasinghe, 2021). Globally, about 54% of these people live in cities; however, as an outcome of rapid urbanization, this is expected to grow to 66% by the end of 2050 (Ni et al., 2019). Population growth is a matter of great concern because rapid population growth and its uneven distribution coupled with rising average income globally are increasing the worldwide demand for food and accelerating the rate of degradation of natural resources, such as land and water, through the additional pressure exerted on them (Abu Hammad and Tumeizi, 2010).

Land is a finite natural resource, with its availability for agriculture limited, as it is required for other purposes as well. Therefore, it will be very difficult to develop additional arable land to grow more crops and meet the rising demand for food by expanding land-dependent conventional agriculture. On the other hand, intensive use of fertilizer without cultivating additional land is unlikely to enhance the yield above a certain point (Zhang et al., 2010). Furthermore, such practice accelerates soil degradation by causing depletion of natural resources (Chen, 2007).

Like land, fresh water, another critical input for conventional agriculture, is also finite in nature and limited in supply. Additionally, its global distribution is uneven and agriculture alone accounts for 69% of the world's freshwater usage (Kwon et al., 2021). Excessive withdrawal of artesian fresh water for irrigation purpose has already led to the large scale depletion of available surface water (Tularam and Krishna, 2009), impacting other crucial areas, such as the energy sector, which also needs this resource. For example, in India, water shortage or its unavailability in 2016 alone has resulted in a loss of 4 terawatt hours of thermal power generation (Luo et al., 2018). Hence, it will be very hard for conventional farming systems to obtain additional allocation to produce more crops.

Hydroponics is a soil-less cultivation system that holds great promise as an adjunct to conventional systems for enhancing crop yield without requiring any cultivable land. Hydroponics is reported to produce approximately 30–50% higher plant growth rates than conventional systems (Huo et al., 2020; Supraja et al., 2020; Majid et al., 2021;). A well-controlled, optimized and stress-free growth environment created in hydroponic cultivation systems can produce 7.7–11 times more crops than the equivalent area-based conventional systems (Jovicich et al., 2007). Therefore, such hydroponic systems can greatly assist in securing food for all in a sustainable manner. In addition, these systems offer scope for recirculation of nutrient solution and the reduction of evaporative water loss through use of greenhouse structures. By adopting these two measures, hydroponics be used to reduce the water demand by 13 times compared to the conventional cultivation system (Barbosa et al., 2015). Hence, in order to meet the high demand for freshly produced fruits and vegetables, hydroponic cultivation would be an ideal choice, especially in cities where the demand is high due to rapid urbanization (Ni et al., 2019) and there have been changes in food habits induced by the overall increase in the average income (Schreinemachers et al., 2018). Furthermore, these systems provide direct economic and environmental benefits by shortening the supply chain and reducing the cost of packaging, processing and transportation. In addition, using a hydroponic system as an on-site nutrient recovery treatment, by replacing the nutrient media with partially treated nutrient-rich wastewater, can cut down the cost of nutrient while increasing the water availability, without consuming any additional energy for water treatment. Notably, 80% of total freshwater withdrawal goes back to the environment as wastewater, raising environmental concerns such as eutrophication and nutrient loss (United Nations World Water Assessment Programme, 2017). Reclamation of water from the waste stream through nutrient removal demands a large amount of energy, with up to 0.5 kWh/m^3 energy annually for the removal of 0.025 Mt of nitrogen and 0.005 Mt of phosphorous (Acién et al., 2016). Therefore, such a cultivation system where hydroponics has been integrated with wastewater treatment is becoming more important now than ever before.

Scientometric analysis involves study based on the bibliographical data in published articles in a particular research area, which gives an overall picture of the current research trends, predominant research areas, most impactful authors and their contribution in that area along with their affiliated organizations and countries (Chen and Song, 2019; Brindha et al., 2022). In the past few years, there have been a few bibliographical studies conducted on food security (Azra et al., 2021), on the evolution of urban agriculture (Wang et al., 2018) and on the sustainability of modern agriculture (Zhang and Li, 2018). However, to the authors' knowledge, no scientometric study has been reported to date, in which hydroponics has been examined as a means of boosting crop production while considering its possible positive impacts on water and energy resources to secure food for everyone, while managing these limited resources sustainably. Similarly, there has been no reported study scrutinizing the advances made in the field of hydroponics toward a sustainable way of farming.

Therefore, the current scientometric study was carried out to contribute to understanding the current prospects of hydroponics, as an adjunct to conventional agricultural systems, in achieving food security and visualizing the advances it requires to overcome its present limitations and thus realize its potential as a sustainable way of farming.

Materials and Methods

The methodology adopted was divided into two sections: 1) scientometric analysis, to identify research trends and knowledge gaps; and 2) strengths, weaknesses, opportunities and threats (SWOT) analysis, to evaluate the prospects for hydroponics. The scientometric analysis methodology was broadly divided into three segments: 1) data collection; 2) data processing; and 3) visualization and interpretation of the whole dataset. A detailed description of the methodology is provided in Fig. 1.

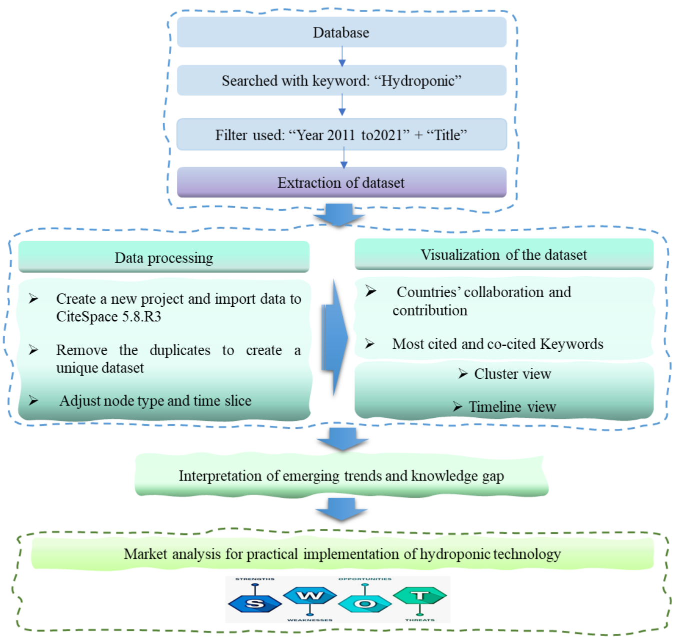

Fig. 1 Flowchart of overall methodology used for scientometric analysis (data collection and interpretation using *CiteSpace*) and strengths, weaknesses, opportunities and threats (SWOT) analysis

Data collection

Literary references were collected of hydroponic technology over the period 2011–2021 from two online repositories: Scopus and Web of Science (WoS). Based on a search using the keyword "hydroponic", 11,912 articles were found. Since this number of hits was very high, the search was subsequently restricted to only those articles having the keyword "hydroponic" in their title to increase the relevance of the dataset. In all, 2,725 articles were found within the selected time period from these two databases. The obtained dataset contained various types of documents such as research articles, conference papers and book chapters.

Data processing

CiteSpace 5.8 R3 is a Java-based open access software that uses bibliographical data to perform a detailed literature review (Chen, 2016). The output from this package provides a comprehensive view of the overall development of a particular research field (including pivotal points), which helps in identifying emerging research topics via easy graphical representations (Chen and Song, 2019). After the collection of the data, all the documents were fed into the CiteSpace 5.8 R3 software and were converted into a single file format. By eliminating any duplicates from the dataset, 2,447 unique articles were obtained and they were considered for further study.

Data visualization

The data obtained were visualized and interpreted using a cluster analysis technique, where each cluster represented a unique research domain, with interaction between two clusters signifying the existence of a correlation between them (Chen, 2006). Analysis of the data in CiteSpace 5.8 R3 was carried out using different nodes such as "countries", "keywords", and "articles" (Chen et al., 2023; Ge et al., 2023). Nodes such as "countries" helped in analyzing the contribution and collaboration of different countries in the selected field. The most impactful (most cited) articles were traced using the node "article" and then combining this knowledge with the most frequently used keywords (obtained using the node "keywords"), knowledge about the evolution and dynamics of this research area was obtained. Subsequently, these results were further validated and explained using several scientific parameters such as citation burst, strength and degree.

The scientific parameters used for the scientometric analysis of the research on hydroponic technology are briefly discussed below.

Relative growth rate

The relative growth rate (RGR) is a growth indicator of a particular research area that shows the overall increase in the number of published articles per time unit. The RGR was calculated using Equation 1:

$$\mathrm{RGR} = \frac{\ln W_2 - \ln W_1}{T_2 - T_1} \tag{1}$$

where W_1 and W_2 are the total numbers of published manuscripts at time T_1 and T_2, respectively, and $(T_2 - T_1)$ is the period during which the particular study was conducted (Rathika and Thanuskodi, 2021).

Doubling time

The doubling time (D_t) another growth indicator, is directly correlated with the RGR. It represents the amount of time the research field takes to double its total number of publications and was calculated using Equation 2 (Rathika and Thanuskodi, 2021):

$$D_t = \frac{\ln 2}{\mathrm{RGR}} \tag{2}$$

where ln is the natural logarithm.

Citation count

The citation count indicates the impact and relevance of a published article (Tundup et al., 2021) based on the total number of citations gained by a particular article over the studied period.

Citation burst

The citation burst is a factor indicative of the impact of an article by passively indicating research hotspots in a particular period. It is defined as the sudden increase in the citation count of a specific published article, journal, author or keyword, indicating a rapid increase in interest in that particular area (Tundup et al., 2021).

Results

Field growth over time and publication distribution in different subject areas

The first article on hydroponics was published in 1950; however, the field only started to flourish after 1990. Publication growth, as an indicator of the field's relevance indicated that from 2011 to 2021, a large number of articles were published with the number increasing annually, indicating growing interest in the field of hydroponics along with its technological progress (Fig. 2A). The average positive RGR value of 0.315 and a mean doubling time of 2.560 yr indicated the constant growth of this field over the period 2011–2021.

Articles collected from Scopus and WoS were analyzed using the node "category" and were divided into different subject categories. "Agriculture" and "Environmental Science and Ecology" were the two most explored areas in the field of hydroponic technology, accounting for approximately 17% and 10%, respectively, of the total published articles (Fig. 2B). In addition, "Plant science", "horticulture", "agronomy" and "food science and technology" were in the top-10 most explored subject areas. However, the very limited contribution in the area of business and management suggested a lack of exploration of the economic aspects of this technology.

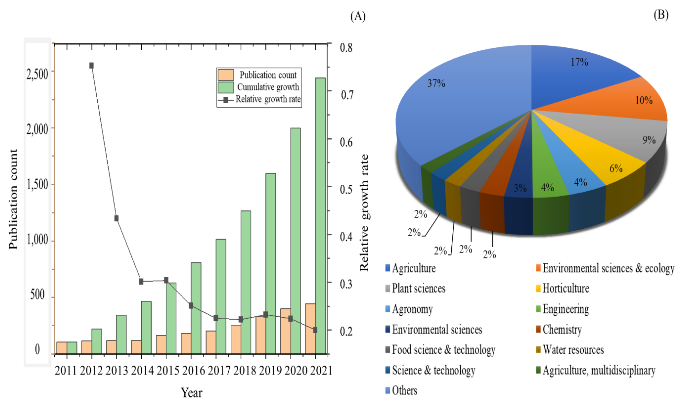

Fig. 2 Field growth and publication distribution in hydroponics by: (A) year (2011–2021); (B) different subject categories

Analysis of contribution of different countries to hydroponics

Worldwide research on hydroponics during in 2011–2021) was investigated based on scientometric analysis and the results are presented in Fig. 3. Based on these results, globally more than 70 countries have contributed to the field of hydroponic research. The cluster analysis showed that during the study period, the USA had the most prominent node with the largest contribution (14%), followed by China (12%) and Brazil (11%). Notably, countries suffering from water scarcity or extreme environmental conditions cannot entirely depend on conventional agriculture due to the shortcomings mentioned previously and could have contributed to contributing more to this field.

Fig. 3 Publication contributions of various countries in hydroponics research from 2011 to 2021, based on data sourced from Scopus and Web of Science

For example, North China often faces the issue of water scarcity due to the uneven distribution of water resource across the country. It has been reported that one-half of the population there suffers from water scarcity throughout the year (Ma et al., 2020). Water availability is not an issue in Brazil. However, tropical or sub-tropical weather coupled with climate change due to global warming is the main challenge regarding the continued use of conventional methods (Filho and Moraes, 2015). Apart from this, uncontrolled withdrawal of artesian fresh water for agricultural purposes is a cause for concern in some countries, such as India, Pakistan and Iran, which are already under high water stress. Therefore, the researchers in these water-stressed countries have started paying more attention to alternative methods of agricultural and inventing new technologies in this area to increase both the efficiency and sustainability of the process. In this context, hydroponics can be of great help. It has been observed that leafy vegetables, such as spinach, require 8.3 L of water to produce 1 kg of plant biomass in soilless cultivation compared to 106 L in soil-based farming (Sambo et al., 2019). In India, (which ranks 13th among the most water-stressed countries in the world), water scarcity has reached an alarming situation because of the excessive population pressure there (Wahi, 2022). India's 7th ranking in the top-10 contributing countries with a share of around 4% in the global total is a reflection of this concern. In response, there was citation burst in 2017 in India, indicating they too had started taking an active interest in alternative agricultural practices such as hydroponics.

Analysis of most impactful articles in hydroponics

Table 1 provides a list of the articles that have received the maximum number of citations in the past one decade. These articles have dealt with some key issues concerning hydroponics, such as sustainability, stability against new-age pollutants, bio-fortification and automated plant management, that can open up new horizons for soilless farming to play an important role in its future development. The most cited article, authored by Barbosa et al. (2015) analyzed the sustainability of a soilless cultivation system by comparing the water and energy consumption levels of hydroponics with those of conventional agricultural practice. These authors showed that while hydroponic cultivation of lettuce could produce approximately 11 times higher yield with 13 times less water than conventional agriculture, it required 82 times more energy to maintain the optimal temperature inside the cultivation room. This result indicated that even though the hydroponic system was capable of substantially improving the yield, the increased energy requirement might be an obstacle to attaining the sustainable food production goal. Therefore, more studies are required to identify the best ways to lower the energy consumption by using different renewable energy sources.

Table 1 List of top-10 most impactful articles in hydroponic technology research

Article title	Citation count	Publication year	Observation	Reference
Comparison of land, water and energy requirements of lettuce grown using hydroponic versus conventional agricultural methods	675	2015	Hydroponic cultivation can produce around 11 times higher yield, with 13 times less water and 82 times higher energy consumption	(Barbosa et al., 2015)
Automated system developed to control pH and concentration of nutrient solution evaluated in hydroponic lettuce production	303	2012	An automated system was successfully developed for efficient and constant monitoring of the pH and conductivity of the nutrient solution to reduce human intervention.	(Domingues et al., 2012)

Table 1 Continued

Article title	Citation count	Publication year	Observation	Reference
Silica nanoparticles for increased silica availability in maize *(Zea mays*. L*)* seeds under hydroponic conditions	255	2012	Application of silicon dioxide nanoparticles can increase the silica availability compared to other bulk sources, which can improve maize seed germination rate	(Suriyaprabha et al., 2012)
Potential effect and accumulation of veterinary antibiotics in *Phragmites australis* under hydroponic conditions	250	2013	*Phragmites australis* can tolerate different antibiotics and accumulate in the plant biomass in root > leaf > stem sequence.	(Liu et al., 2013)
Protocol: optimizing hydroponic growth systems for nutritional and physiological analysis of *Arabidopsis thaliana* and other plants	243	2013	A cost effective and versatile hydroponic system was developed for analyzing plant physiology and nutrient management	(Conn et al., 2013)
Effects of foliar application of some macro- and micro- nutrients on tomato plants in aquaponic and hydroponic systems	236	2011	Foliar spray application of magnesium and iron increases leaf chlorophyll, and application of magnesium, potassium and zinc increases the yield.	(Roosta and Hamidpour, 2011)
Influence of two types of organic matter on interaction of CeO_2 nanoparticles with plants in hydroponic culture	212	2013	The presence of different organic acid (fulvic acid and gum arabic acid) affects accumulation of CeO_2 in the roots, with accumulation highest in absence of any organic acid, followed by fulvic acid and gum arabic acid.	(Schwabe et al., 2013)
Water and nutrient use efficiency of a low-cost hydroponic greenhouse for a cucumber crop: An Australian case study	200	2011	Partial recirculation of the nutrient solution was able to reduce the water efficiency usage by 33%, without showing any inhibitory effect on plant growth.	(Grewal et al., 2011)
Assessment of biofortification with iodine and selenium of lettuce cultivated in the NFT hydroponic system	163	2014	Application of 1.0 mg/L iodine and 0.5 mg/L selenate in nutrient solution had no negative impact on plant growth, while foliar spraying achieved higher biofortification than from nutrient solution.	(Smoleń et al., 2014)
Comparative effects of selenite and selenate on growth and selenium accumulation in lettuce plants under hydroponic conditions	194	2013	Biofortification or nutrient enrichment in lettuce can be achieved by adding selenium (an essential micronutrient for humans and plants) is the form of selenite or selenate, in the nutrient solution, at a concentration lower than 15 μM	(Hawrylak-Nowak, 2013)

In recent years, a major environmental issue has arisen due to the presence of pharmaceutical compounds, such as antibiotics and engineered nanoparticles, in different aquatic systems. Therefore, it has become very important to understand their tolerance limit, the mechanism of their uptake and accumulation by the plants and their adverse effects on plant growth. Liu et al. (2013) investigated the effect of three different veterinary antibiotics (sulfamethazine, ciprofloxacin and oxytetracycline) on *Phragmites australis*. These workers observed that antibiotic concentrations >10 parts per million (ppm) retarded root growth and chlorophyll production, while a milder dosage of ≤1 ppm produced hormesis. In addition to the investigations on antibiotics, several studies have examined the interaction of nano-particles with plants in a hydroponic system (Schwabe et al., 2013; Suriyaprabha et al., 2012). In one such study, Schwabe et al. (2013) detected the presence of nanoparticles in the pumpkin shoots after the plants had been exposed to 100 ppm uncoated CeO_2 nanoparticles for 8 d. Suriyaprabha et al. (2012) reported that silica nano-particles extracted from rice husks helped to induce seed germination by 95%. Nano-particles have been observed to interact with plants in many ways, though some literature reports indicated that compared to bulk compounds, the nanoparticles produced from the same compound may pose greater risks including phytotoxicity to plants (Musante and White, 2012; Landa et al., 2017;).

Essential trace elements, such as iodine or selenium, are important for human health (Lossow et al., 2019) and therefore need to be incorporated in the daily human diet. This can be easily achieved by bio-fortification of crops using these compounds. Hawrylak-Nowak (2013) observed a concentration dependent effect of selenite and selenate on plants, reporting that at a concentration of 15 µmole/L of nutrient solution, such compounds exhibited phytotoxicity, while below this level they induced plant growth and increased uptake by plant biomass. The mode of application of such components was also investigated (Roosta and Hamidpour, 2011; Smoleń et al., 2014). Direct application via a foliar spray proved more effective than application via a nutrient solution in achieving a higher level of bio-fortification. Furthermore, Roosta and Hamidpour (2011) reported that foliar spray of some essential macro- and micro-elements, such as potassium, iron, magnesium and boron, was effective in inducing plant growth.

Table 1 indicates very clearly that during 2011–2021, one of the most focused areas of the field integration of hydroponics has been automation to reduce human intervention by lowering the need for constant monitoring of the nutrient availability. Domingues et al. (2012) highlighted the use of different sensors and algorithms for developing automated hydroponic systems. In addition, many research studies were conducted on nutrient solution management techniques to reduce environmental concerns of excessive nutrient pollution and to increase the efficiency of water and nutrient usage. In one such study, Grewal et al. (2011) showed that partial re-circulation could reduce the water requirement by 33% without having any inhibitory effect on plant growth.

Keyword analysis to investigate development of hydroponic research

Analysis of keyword clusters based on research similarity and citation burst clarified some key issues: 1) the evolution of one particular research area and the associated research dynamics; 2) the shift in the research focus at different times during the course of development; and 3) current research trends. In the present study, keyword cluster analysis was used to construct a timeline of the evolution of the research field (Fig. 4) and to validate it using keyword analysis.

From the citation burst analysis conducted since 2011 (Table 2), a citation burst was observed for each of the keywords "phytotoxicity", "phytoremediation" and "accumulation", indicating an extensive use of hydroponic systems in the study of phytotoxicity of different pollutants. An investigation conducted by McComb et al. (2012) that examined the impact of lead (in the concentration range 0.1–20 µmol/L) on *Sesbania exaltata* showed that when exposed to lead, a major portion of the lead taken up by the plants accumulated in the roots,

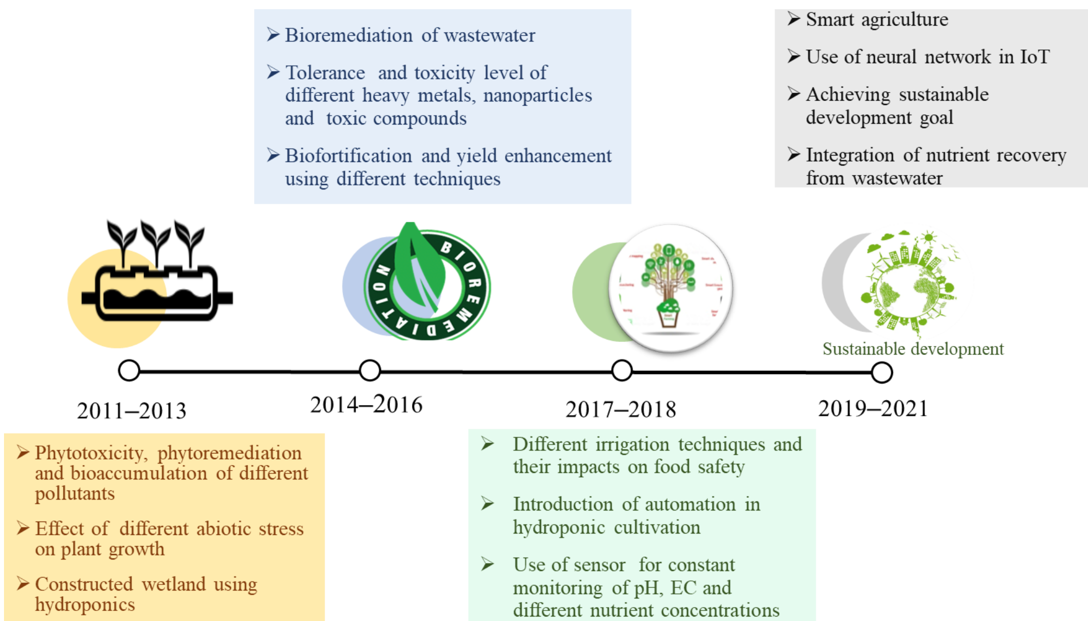

Fig. 4 Evolution of hydroponics technology from 2011 to 2021, where IoT = Internet of Things

with little being translocated to other plant parts. However, lead is toxic to plants and exposure to lead caused browning of the root, mild chlorosis and leaf abscission at higher concentrations in the investigated range. The term “constructed wetland” had a citation burst strength of 5.85, which was the 4th highest citation burst strength since 2013, pointing to the growing research interest in wastewater remediation using hydroponic technology. In 2014, researchers began focusing on the tolerance levels of plants to different pollutants and also on parameters such as “gas exchange rate” (burst strength 3.33), “chlorophyll fluorescence” (burst strength 3.02), “oxidative stress” (burst strength 2.921), production of “antioxidant” (burst strength 3.5) to measure the effect of various abiotic stresses on plants. The citation burst strength of 2.59 for the keyword “selenium” indicated increased research focus on the application of micronutrients, such as selenium, to enhance the yield by inducing stress tolerance capacity.

From 2014 onward, researchers focused on achieving better nutrient management and higher yield through constant monitoring of parameters such as pH and electrical conductivity. In addition, the researchers started exploring techniques including the application of various nanoparticles for yield enhancement. Research was also conducted to identify the tolerance limit and toxicity limits for different compounds along with their optimum concentrations to enhance plant growth. In addition, the cultivation of different microbes, such as bacteria and microalgae, gained much attention during the period. Analysis of cluster #3 “constructed wetland” (cluster size 75) showed the association of keywords under this cluster such as “pollutant removal”, “nitrogen”, “phosphorus”, “eutrophic water”, “microbial community” and “wastewater management” (Fig. 5). This result indicated that research during this period focused on using hydroponic technology in constructed wetlands, along with microbial communities, to remove pollutants, including various nutrients and to reduce the risk of eutrophication (Chen et al., 2014; Al Chami et al., 2015). The citation burst data presented in Table 2 cross-validated this observation.

Table 2 Top 25 keywords with strongest citation bursts in hydroponics*

Keyword	Strength	Begin	End	2011–2021
lycopersicon esculentum	11.42	2011	2014	
metabolism	7.33	2013	2016	
microbiology	6.34	2014	2016	
constructed wetland	5.85	2013	2016	
pollutant removal	5.43	2015	2017	
growth rate	5.38	2012	2016	
root	4.96	2014	2016	
accumulation	4.94	2011	2015	
dicotyledon	4.82	2011	2015	
wetland	4.77	2013	2017	
sodium	4.39	2014	2016	
automation	4.38	2017	2019	
ion selective electrode	4.33	2017	2021	
internet of things (IoT)	4.23	2017	2019	
groundwater	4.1	2015	2017	
wastewater	4.09	2013	2016	
water pollution	4.08	2013	2018	
growth response	4.06	2015	2017	
root exudate	4.06	2015	2017	
antioxidant enzyme	4	2013	2015	
performance	3.94	2015	2017	
genetics	3.85	2016	2018	
waste component removal	3.85	2016	2018	
soilless culture	3.81	2012	2014	
phytoremediation	3.79	2011	2013	

*Data represents keywords with strongest citation bursts during 2011–2021.
Red segments indicate specific years or periods during which these keywords experienced a sudden increase in number of citations.

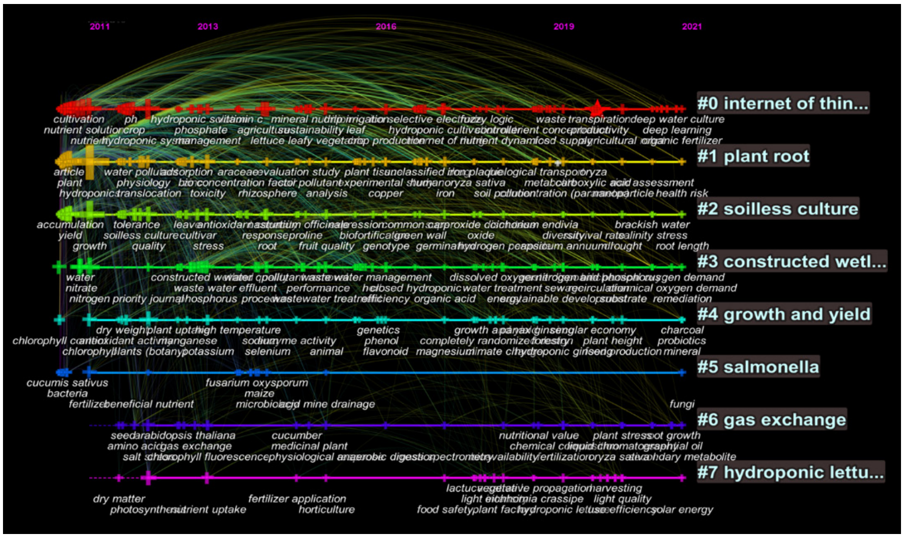

Fig. 5 Timeline overview of keywords evolution in hydroponics technology 2011–2021, based on data sourced from Scopus and Web of Science

Constant monitoring of the environment requiring skilled manual labor was identified as one of the major problems for the hydroponic cultivation system. Therefore, from 2017 onward, there was a focus on automation techniques for monitoring various parameters in the nutrient solution. This fact was validated by the citation burst for the keywords, "automation" (burst strength 4.38) and "internet of things" (IoT; burst strength 4.23) in the post-2017 period. The largest cluster #0 IoT (cluster size of 134) was also a clear signal that automation was an attractive research area in the last few years. Development of a fully automated system through the introduction of sensors, such as "ion-selective electrode" (burst strength 4.33) and "neural network" (burst strength 3.16) in an IoT-based hydroponic setup was an important research area in the field of hydroponics. Additionally, the use of hydroponic cultivation for "sustainable development" (burst strength 3.95) emerged as a current research hotspot. The researchers explored several alternative nutrient sources, such as sewage, organic waste and nutrient-rich effluent from aquaculture, to achieve the goal of sustainability.

Strengths, weaknesses, opportunities and threats analysis

A SWOT analysis was performed (Fig. 6) to assess the prospects of hydroponics in its present state.

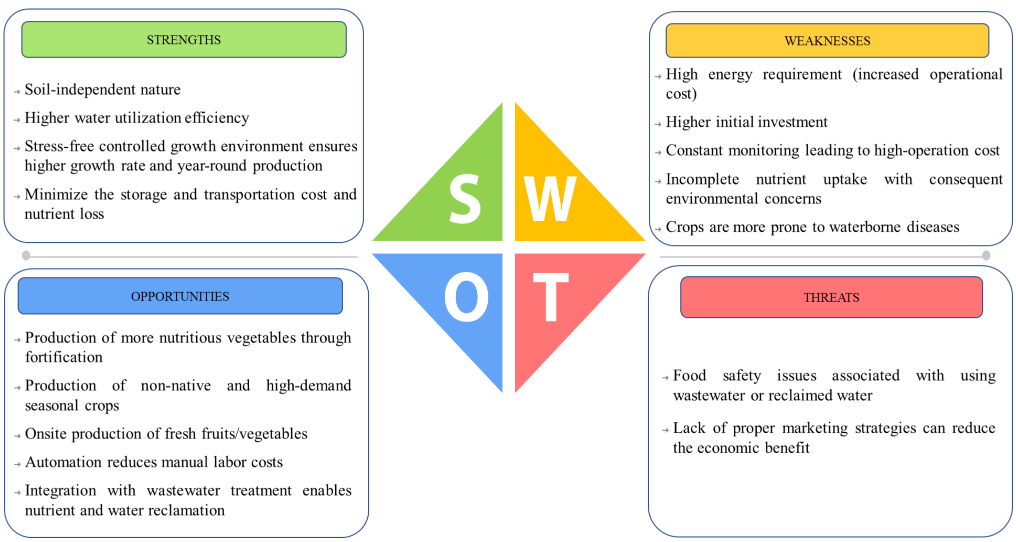

Fig. 6 Strengths, weaknesses, opportunities and threats (SWOT) analysis for commercial implementation of hydroponic technology

The major strength of hydroponics lies in its strict control over the inputs and cultivation environment, which eliminates the possibility of facing abiotic stress or pest attack, or both and thereby produces a 30–40% higher growth rate. Another area of strength for this system is its ability to supply promptly freshly produced fruits and vegetables to urban markets with minimal storage, transportation and loss of food value. In addition, hydroponics offers scope for growing vegetables in a greenhouse year-round, even in colder countries where the growing session is restricted to summer.

A large initial investment and high energy consumption (leading to increased operational costs) are considered major deficiencies of the system (Kaouche-Adjlane et al., 2016). Another possible weakness of hydroponics could be doubts in the minds of people generally about the acceptability of the crops produced through a non-conventional system of farming.

Despite these challenges, a hydroponics system of farming presents many opportunities. These include the bio-fortification of crops by enhancing essential micronutrients such as selenium, automation-driven cost-cutting by reducing manual labor requirements and the potential for nutrient recovery and water reclamation from wastewater. In addition, changes in lifestyle and customers' preference for healthy, nutritious, pesticide-free freshly produced vegetables may help in expanding the hydroponic market in future, as is happening elsewhere in Europe and the Asia-Pacific region (Nisha et al., 2018). Furthermore, huge dividends may accrue from the identification of target customers and target fruits or vegetables (non-native vegetables or crops having higher market demand) and an initiative to educate customers on the health benefits of hydroponically grown crops (Prayoga and Putra, 2020). In fact, Narine et al. (2014) showed that young people from the high-income group-with a strong educational background could be target customers for these products. Their research survey concluded that the customers were willing to pay a 4% premium price for hydroponically produced vegetables based on their superior quality. Improvements in these areas could potentially boost the global hydroponic market, which is presently worth approximately USD 9.5 billion (Velazquez-Gonzalez et al., 2022).

Threats to hydroponics may come in the form of a concern for food safety; however, this is related to the use of reclaimed water only and is a technical issue. Consequently, with further development in technology, this issue may lose its relevance.

Discussion

Unrealized potential and plausible future developments

Projected population growth and urbanization, along with issues such as climate change and the depletion of natural resources, have driven research activities to improve hydroponic farming systems, to meet rising food demand. While progress has been made in some areas, the true potential of hydroponics has remained unrealized. three key areas for future development were identified, based on the scientometric analysis: 1) energy management; b) water management; and c) hygiene and food safety. The subsequent sections summarize the reported advances and the developments envisaged in each of these areas.

Energy management

High energy consumption (reaching up to 40% of the total operational cost) is a major concern in hydroponic cultivation (Liaros et al., 2016). Despite being a high yielding system (as mentioned in the earlier discussion), the energy consumption associated with hydroponics surpasses that of conventional agriculture. Hence, lowering the energy requirement or using renewable energy sources is expected to increase the sustainability of the system. Barbosa et al. (2015) reported that year-round lettuce production consumes the most energy for temperature maintenance (74,000 ± 10,000 kJ/kg), followed by artificial lighting (15,000 ± 2100 kJ/kg) and water circulation (640 ± 120 kJ/kg). This high energy requirement could be lowered in several ways. For example, replacing conventional heating (using a fuel heater), with a heat pump to maintain the temperature could reduce the energy consumption by 25–65%, increase energy utilization efficiency up to 2.6-fold and reduce carbon emissions by 56–79% (Avgoustaki and Xydis, 2020). More such interventions in this area will help to increase energy utilization efficiency and reduce the system's ecological footprint. Apart from this, energy requirements could be further lowered by integrating renewable energy sources, such as solar panels, with hydroponics (Delrue et al., 2021; Putera et al., 2015; Snow and Ghaly, 2008) or using advanced greenhouse designs (Baddadi et al., 2019). Likewise, a few other strategies that might be helpful in enhancing the system's energy efficiency include the optimal use of energy-efficient light-emitting diode lights (Namgyel et al., 2019; Zheng et al., 2019), maximal use of natural daylight (such as from using solar pipes and optical fibers) and photoperiod optimization

(Avgoustaki, 2019) and optimization of the wavelength of the artificial light (to obtain a higher yield).

Water management

The spent solution discharged from a commercial hydroponic system contains around 200–300 mg/L of nitrate and 30–100 mg/L of phosphate (Saxena and Bassi, 2013). This can result in monthly nutrient losses of up to 230 kg/ha nitrogen, 54 kg/ha phosphorus and 413 kg/ha potassium in open systems (Breś, 2009). Closed-loop water circulation systems have been attempted to mitigate this issue; However, the scope of such mitigation has been limited due to the accumulation of sodium chloride (from nonessential ions such as sodium or chloride present in the irrigation water) and other toxic allelochemicals, such as benzoic acid and malonic acid released by the plants in the nutrient solution (Asaduzzaman and Asao, 2012; Carmassi et al., 2003; Sambo et al., 2019) together with the increased risk of disease spreading. Several conventional end-of-the-pipe treatments, such as denitrification (Rodziewicz et al., 2019) and wetland construction (Gorgoglione and Torretta, 2018), have been found unsuitable either because of their high environmental impact or large space requirement. In addition, inefficient phosphate recovery and long retention times were reported as major drawbacks. While Delrue et al. (2021) improved phosphate recovery with alkaline pre-treatment, they could do so only by adding an extra operation. Thus, further advancements are required in process optimization and biotechnology-based routes (including microalgal remediation).

Using untreated or partially treated wastewater in hydroponics can reduce nutrient requirements and achieve wastewater remediation. For example, cultivation of barley in aquaculture effluent reduced the nitrogen requirement by > 75% (Snow and Ghaly, 2008) and vetiver grass cultivation in brewery wastewater cut-down the nitrogen and phosphorus requirements by 58% and 63%, respectively, while achieving 73% and 97% reductions in biological oxygen demand (BOD) and total dissolved solids (TDS) (Worku et al., 2018). These findings highlight the potential of hydroponics to reduce nutrient and freshwater requirements through a decentralized wastewater treatment system, though the results will depend on factors such as plant type, nutrient composition, nutrient load (which depends on the effluent source) and operational conditions (Magwaza et al., 2020). Despite health and safety concerns (discussed in the following section), hydroponic farming with wastewater presents major opportunities for water economy and wastewater reclamation, necessitating further research focused on conserving freshwater as a finite resource.

Hygiene and food safety

Hygiene and food safety issues in hydroponics arise primarily from the use of partially treated or untreated wastewater, which poses health risks to both growers and consumers through direct contact with the wastewater or the crops cultivated using that wastewater, or both. While all crops grown with untreated or partially treated wastewater are susceptible to contamination, herbs and leafy vegetables present higher risks due to the nature of their production and associated activities, increasing pathogen contamination risks (Magwaza et al., 2020). Since a health risk may originate from both the wastewater and crop, risk analysis focuses on factors such as pathogen levels in untreated wastewater, pathogenic bacteria concentrations (for example, *E. coli*), pathogen transfer rates to crops, consumption patterns and dose-response data (Keuckelaere et al., 2015). Contamination risks can be mitigated by applying guidelines suggesting secondary treatment with disinfection to reduce the pathogen count (Alcalde-Sanz and Gawlik, 2017), testing for some reference pathogens (such as *Campylobacter* sp. or *Salmonella* sp. for bacteria and *Cryptosporidium* for parasitic protozoa and helminths), selection of crops resistant to contamination and optimization of the crop-withholding period before consumption (Keuckelaere et al., 2015) Ndulini et al. (2018) evaluated the potential of hydroponics for pathogen removal and reported a 92.77% fecal coliform removal efficiency, which supported resource-efficient farming. Future research should focus on factors, such as plant type, wastewater characteristics and pre-treatment methods, to ensure food safety and to optimize nutrient and water management.

Sustainability check

Any technological advancements or changes will have an impact on the environment, economy and society. With sustainability now a key criterion for progress, technological changes are only acceptable if they are also sustainable. Thus, evaluating sustainability is crucial. To provide a complete picture of the current sustainability status of hydroponic farming systems, this section summarizes studies from the period 2011–2021, assessing their sustainability from both economic and environmental perspectives.

Economic perspective

From an economic perspective, hydroponics is a high-input-high-output system, yielding high productivity per unit area but requiring substantial initial and operational costs. Pascual et al. (2018) showed that establishing a vertical hydroponic system over 2,500 m² required an initial investment of approximately USD 44,000, which is some 5–10 times higher than for conventional farming investments, posing a major barrier for small-scale farmers and suggesting the need for governmental financial incentives to promote this technology. Additionally, large-scale hydroponic farming consumes a large amount of energy just to maintain the optimum temperature alone, which increases the production cost considerably. Quagrainie et al. (2018) reported that in hydroponic farming, energy consumption constituted 25% of total production costs, while labor charges accounted for 65%. Hence, implementing automation and judiciously utilizing renewable energy at various stages could considerably reduce production costs. While the studies cited above give some idea about the economic aspects of hydroponics, they are of little value in the decision-making process. Therefore, more comprehensive techno-economic analysis studies are necessary to fully understand cost distribution and to assess the overall economic feasibility of hydroponics.

Environmental perspective

Life cycle analysis (LCA) is a preferred method for evaluating environmental sustainability, such measuring a carbon footprint of a process within a predefined system boundary. The energy source for hydroponic cultivation plays an important role in this regard. Chen et al., (2020) used a cradle-to-gate approach to compare the environmental impact of hydroponic and aquaponic systems under identical conditions, reporting that aquaponic had a 45% lower environmental impact. These authors also noted that using renewable energy (wind power) instead of non-renewable energy (coal power) could make hydroponic systems more sustainable than aquaponic ones. Similarly, Romeo et al. (2018) concluded that renewable, carbon-neutral energy sources improved the sustainability of vertical hydroponic farming systems compared to heated greenhouses and conventional land-based farming. Additionally, several studies reported that the choice of supporting media in hydroponic systems affected their overall sustainability (Martin and Molin, 2019; Toboso-Chavero et al., 2021; Vinci and Rapa, 2019). For example, Vinci and Rapa (2019) showed that replacement of supporting materials such as perlite or rock wool with sand, bark or coconut fiber, could make the food production system more sustainable. Martin and Molin (2019) recommended using paper pots instead of plastic to reduce greenhouse gas emissions. While these studies provided insights into the environmental performance of hydroponic cultivation, they lacked comprehensive LCA (as they do not cover the entire picture) or have been often based on extrapolated results from batch or pilot-scale studies rather than full-scale real-life field data. Therefore, further exploration in this area is necessary to achieve a breakthrough.

Prospect of hydroponics in an inherently uncertain world

While the sustainability check carried out in the previous section further emphasized the inherent weakness of hydroponics in terms of high initial investment, the scientometric analysis for research trends clearly indicated some exciting opportunities that might lead to reductions in both operational costs and environmental impacts, with the concomitant mitigation of any perceived threat of food contamination. Therefore, even though the SWOT analysis identified the existing weaknesses of hydroponics, the system has an excellent prospect of evolving into a sustainable adjunct to conventional agricultural systems.

Concluding remarks

The global issue of food security calls for the production of more crops in a sustainable manner. In this context, this scientometric study was carried out to understand the overall progress and development of hydroponics over the past decade and to examine its utility as an adjunct to the conventional system of agriculture for accomplishing food security. The study revealed that hydroponics is of great utility for countries suffering from water scarcity or extreme environmental conditions. Earlier research on hydroponics focused on issues such as the effects of abiotic stress and mitigation strategies, yield enhancement, bio-fortification, better nutrient management and automated operation. The USA, China and Brazil have led research in this area. However, with the dominant emphasis on sustainability in recent years, some issues have gained importance such as high energy consumption, incomplete nutrient utilization and concern for food safety (when integrated with water reclamation) as they impact the sustainability of hydroponics. Consequently, these are also issues that have restricted the progress of hydroponics, even though there are very good prospects because of its capacity to function without requiring additional land and its ability to produce customized crops, including non-native fruits and vegetables, as and when required. Therefore, future research involving hydroponics is most likely to be pursued to improve the overall sustainability of the system by enhancing nutrient uptake, reducing power consumption, achieving food safety and lowering the initial investment required. In this context, useful research may consider the optimization of the photoperiod and wavelength (for artificial light sources) and designing an appropriate plant for utilization of renewable energy. With further technological advances in these areas, hydroponics is expected to emerge as a sustainable way of farming having overcome all its present limitations.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

The Department of Biotechnology and Medical Engineering of the National Institute of Technology Rourkela providing research facilities. The Ministry of Education, Government of India sponsored the Ph.D. program for the first author.

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