

Role of Hydroponic Farming in Achieving Sustainable Agriculture: A PRISMA Based Meta-Analysis

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ABSTRACT

The hydroponic farming is a soil-less method of cultivating plants by delivering macro and micro-nutrients directly to the roots via a water-based solution. This technique of farming uses up to 90% less water than traditional agriculture farming and allow ten times more yield, making it efficient and sustainable solution for urban agriculture and controlled environment farming. Hydroponic system of farming offers several advantages over traditional soil farming. They recycle and reuse water continuously, using up to 90-95% less water than outdoor cultivation, while delivering oxygen and customized nutrient solutions directly to the roots which can make plants grow 30-50% faster than traditional methods. Their compact designs and vertical stacking methods maximize space efficiency, allowing more crops to be produced in small indoor or urban areas. Because plants are grown without soil, weeds are eliminated and soil-borne peatland disuses are greatly reduced. Indoor climate control also enables years round production regardless of seasonal weather conditions. In this study, relevant papers are selected through **PRISMA** technique based on keywords and title of paper. This is a reviewed paper which examines whether hydroponic plantation method is useful for sustainable agriculture development in India. These selected papers are being reviewed for analyzing the facts that hydroponic planation system can contribute towards sustainability. The expected outcome of the paper is that hydroponic system of plantation offers a promising pathway towards sustainable agriculture by conserving natural resources, increasing productivity and contributing to long-term food security and environment sustainability.

Keywords: Hydroponic, Sustainability, PRISMA, Agriculture, Environment

INTRODUCTION

Modern conventional agriculture faces compounding pressures from escalating land degradation, acute water scarcity, and climate volatility, threatening global food security. In response, hydroponics—a soil-less cultivation methodology that delivers precise nutrient solutions directly to plant root systems—has emerged as a pivotal innovation

in controlled-environment agriculture. By optimizing resource utilization, hydroponic frameworks conserve up to 90–95% more water and deliver significantly higher crop yields compared to traditional soil-based practices, offering a viable pathway for urban farming and land-constrained regions. However, the transition from conventional farming to soil-less technologies involves complex socio-economic, technological, and environmental trade-offs. While smart automated hydroponics and closed-loop systems promise enhanced resource efficiency, issues concerning substantial initial capital expenditure, energy intensity, and technological adoption barriers in developing agrarian economies like India remain critical bottlenecks.

To critically evaluate these dynamics, this study employs a systematic review guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol on Scopus-indexed literature. This paper synthesizes contemporary empirical evidence across resource efficiency, digital technology integration, and policy economics to evaluate the true potential of hydroponic farming in fostering sustainable agricultural development and long-term food security

RESEARCH METHODOLOGY

This present research paper is reviewed-based study that adopts a Systematic Literature Review approach based on Preferred Reporting items for systematic Reviews and Meta-Analysis (PRISMA) technique. The study is based on secondary data collected from the Scopus database. Scopus was selected because it is one of the major international databases for peer-reviewed scientific literature and provides comprehensive bibliographic information, including titles, abstracts, keywords, authors, affiliations, citations, and publication details. A systematic search was conducted in the Scopus database using different combinations of keywords related to hydroponics and sustainable agriculture. The search was primarily performed within the Title, Abstract, and Keywords fields to ensure that the selected publications were directly relevant to the research topic.

The following search combinations and preliminary results were obtained:

Table 1: Description of Words and related Articles

Search Keyword / Search String	Number of Documents
Hydroponic	17430
Hydroponics	12,612
Hydroponic Farming	1332
Hydroponics and Sustainable Agriculture	884
Hyropoinics and sustainability	664
Hydropoic farming and sustainable agriculture	319
Hydroponics and sustainable agriculture in India	34

Source: Author's own tabulation

PRISMA-Based Identification Process

The literature selection process was carried out according to the four major stages of the PRISMA framework:

Stage I: Identification

Initially, a broad search was conducted using the terms **“Hydroponic,” “Hydroponic Farming,” and “Hydroponics.”** This resulted in a large number of records. Subsequently, more specific Boolean search strings were used to identify studies related to sustainability and sustainable agriculture.

The final search string focusing specifically on the Indian context produced **34 documents**.

Stage II: Screening

During the screening stage, duplicate records, irrelevant publications, conference notices, editorial materials, and studies not directly related to hydroponics and sustainable agriculture were excluded.

Stage III: Eligibility Assessment

The full texts of potentially relevant publications were assessed based on predefined inclusion and exclusion criteria.

Inclusion Criteria

- Publications indexed in the Scopus database.
- Studies focusing on hydroponics or hydroponic farming.
- Studies examining sustainability, sustainable agriculture, resource efficiency, water conservation, food security, environmental sustainability, or related dimensions.
- Studies specifically related to India, where applicable.
- Peer-reviewed journal articles and relevant review papers.
- Publications containing sufficient bibliographic and analytical information.

Exclusion Criteria

- Duplicate publications.
- Studies unrelated to agriculture or food production.
- Publications mentioning hydroponics without examining its agricultural or sustainability implications.
- Non-relevant editorials, notes, and incomplete records.
- Studies for which sufficient information was unavailable.

Stage IV: Final Inclusion

After the processes of identification, screening, and eligibility assessment, the final set of relevant studies was selected for systematic review and analysis.

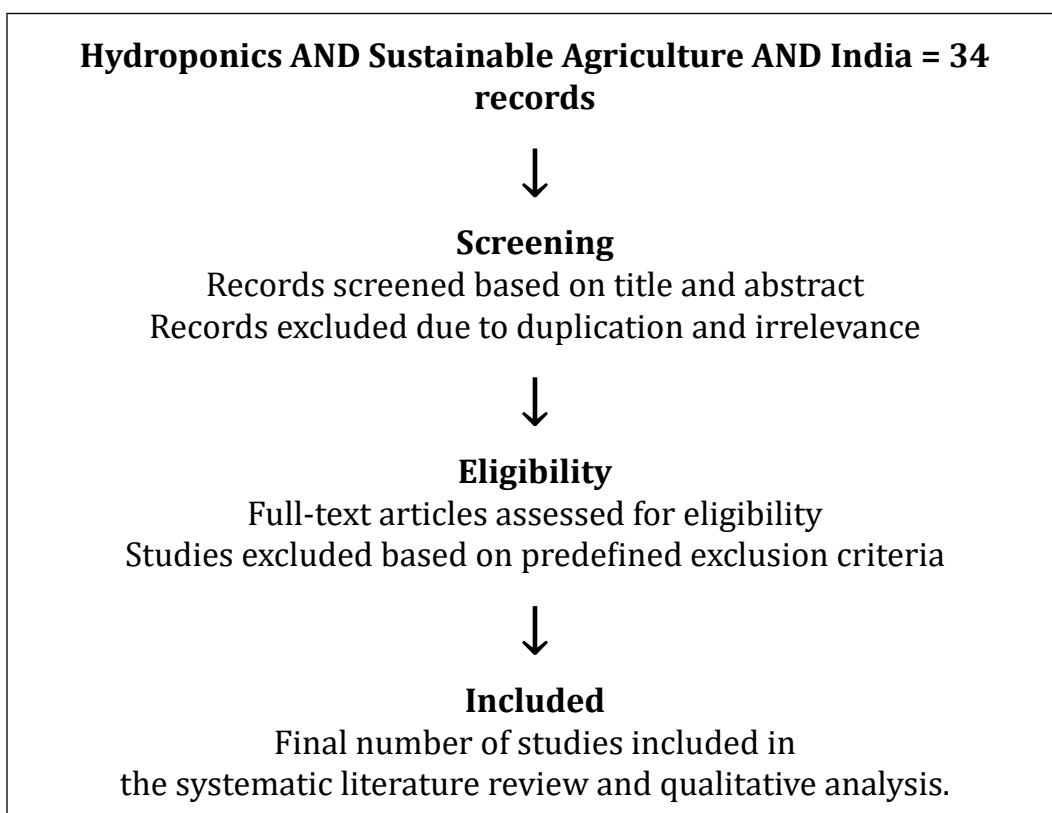
For a study specifically focusing on **hydroponics and sustainable agriculture in India**, the search identified **34 records** at the initial stage. The final number of studies included in the systematic review should be determined after removing duplicates and excluding irrelevant publications through title, abstract, and full-text screening.

PRISMA Flow Diagram

The study may present the literature selection process in the following PRISMA format:

Identification

Records identified through Scopus database search



Note: The exact number at each stage should be inserted after completing the screening and full-text review.

Data Extraction and Analysis

Relevant information was extracted from the selected publications, including:

- Author(s)
- Year of publication
- Country or geographical focus
- Type of publication
- Research objectives
- Hydroponic system studied
- Crops investigated
- Water-use efficiency
- Land-use efficiency
- Energy requirements
- Nutrient management
- Environmental impacts
- Economic feasibility
- Contribution to food security
- Sustainability indicators
- Major findings and recommendations

The selected studies were analysed using **descriptive and thematic analysis**. Descriptive analysis was used to examine publication trends and the distribution of studies, while thematic analysis was applied to identify the major themes emerging from the literature.

The major thematic areas may include:

1. Water conservation and efficient resource utilisation
2. Land productivity and urban agriculture
3. Reduction in soil-related problems and pesticide use
4. Food security and nutritional sustainability
5. Economic feasibility of hydroponic farming
6. Energy consumption and technological challenges
7. Environmental sustainability
8. Opportunities and challenges of hydroponics in India

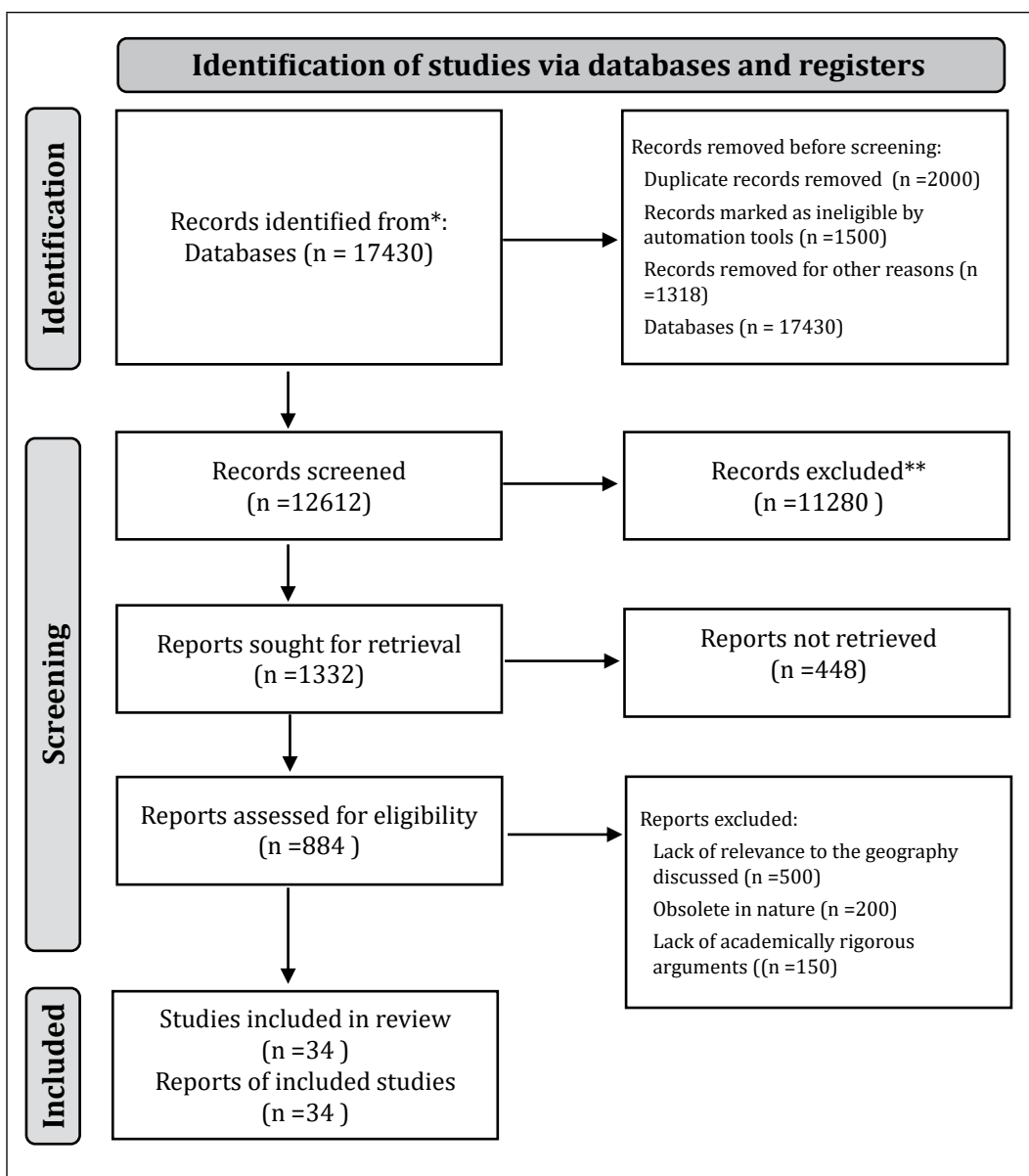


Fig. 1: PRISMA Flow Diagram

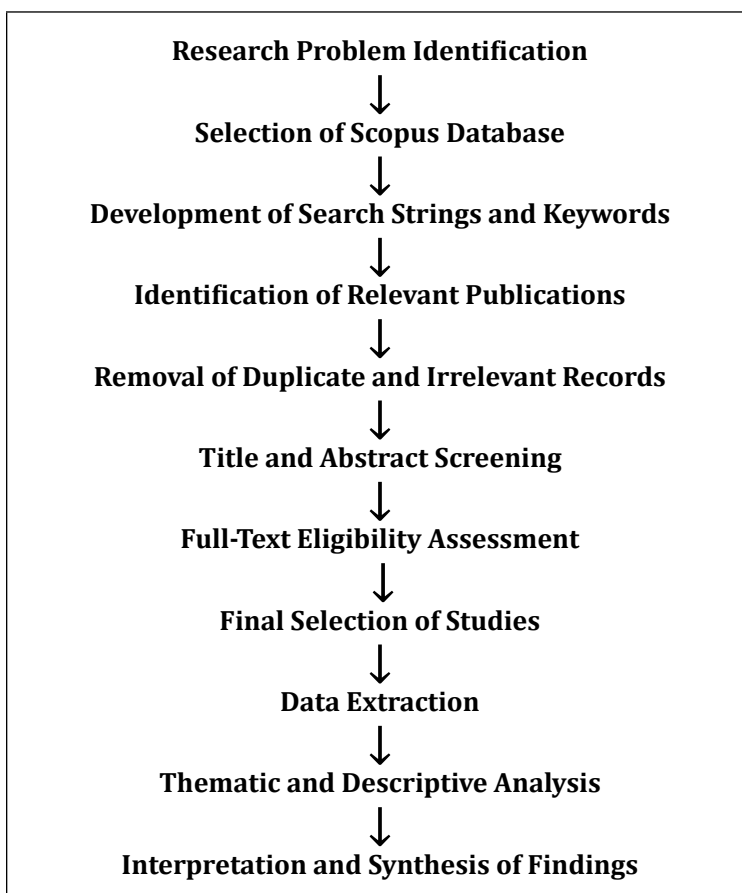
**Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).*

***If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools.*

Source: Author's own formulation using Prisma Framework

METHODOLOGICAL FRAMEWORK

The overall methodological process of the study can be represented as:



REVIEW OF LITERATURE

Thematic and Descriptive Analysis

Smart Hydroponics, IoT & AI Automation

Contemporary literature highlights a critical paradigm shift toward technology-driven Controlled Environment Agriculture (CEA) as an essential pathway to address climate vulnerabilities, land scarcity, post-harvest losses, and global food insecurity. Comprehensive macro-level reviews demonstrate that integrating digital transformation—encompassing Artificial Intelligence (AI), Internet of Things (IoT), robotics, and precision crop monitoring—significantly enhances resource-use efficiency,

crop yields, and environmental sustainability (Camlica & Yaldiz, 2023), with empirical evidence in developing contexts underscoring that institutional support, digital infrastructure, and rural IoT integration are key catalysts for farm-level technology adoption (Rakholia et al., 2024). At the functional level, soil-free agricultural architectures have evolved from foundational microcontroller-based automated setups utilizing basic pH and liquid sensors (Jerusha et al., 2021) toward energy-efficient, outdoor Deep Water Culture (DWC) frameworks utilizing low-power communication protocols like MQTT for real-time microclimate regulation (Subhashini et al., 2024). Furthermore, scholarly synthesis reveals that incorporating computer vision, data mining, and closed-loop urban aquaponic/vertical systems mitigates supply chain friction, minimizes post-harvest wastage, and optimizes spatial land use through circular bio-economy dynamics (Jaiswal et al., 2024; Shukla et al., 2024). Representing the frontier of predictive automation, empirical research validates that deploying advanced multivariate deep learning models—specifically Long Short-Term Memory (LSTM) networks over cloud-integrated IoT sensor arrays—outperforms legacy threshold-based controls, dynamically predicting nutrient requirements to achieve a 27.6% reduction in nutrient waste and a 19.3% yield expansion (Devaraju et al., 2026). Collectively, this synthesized literature confirms that smart, automated, and AI-assisted hydroponics offer a scalable, resource-efficient, and economically viable foundation for sustainable urban food systems.

Agronomic Performance and Cultivar Calibration

Evaluation of contemporary controlled-environment literature in India reveals that hydroponic systems—specifically Deep Water Culture (DWC) and Nutrient Film Technique (NFT)—consistently outpace conventional soil-based agriculture across agronomic performance, resource utilization, and spatial yield density. Empirical evidence demonstrates that recirculating hydroponic frameworks dramatically elevate lettuce (*Lactuca sativa* L.) and leafy greens productivity, achieving up to 3.5 to 4 times higher crop yields while drastically reducing land requirements (up to 65%) and crop growth duration by up to 15 days (Hasan et al., 2026; Majid et al., 2021). Agronomically, cultivar selection and nutrient solution calibration play crucial roles in optimizing economic output; for instance, 'Romain' cultivars demonstrate superior morphological characteristics such as plant height and chlorophyll retention, whereas 'Batavia' optimizes total fresh leaf weight under circulating acidic pH and tailored electrical conductivity (Sahu et al., 2025). Furthermore, system design directly impacts resource optimization, where vertical A-frame NFT models maximize spatial footprint—supporting up to 26 plants per square meter—while generating substantial water savings (64% to 69%) and driving higher concentrations of essential bio-compounds like ascorbic acid and carotenoids compared to soil or aggregate media (Hasan et al., 2026; Thomas et al., 2026). When substrate optimization is paired with precise electrical conductivity (e.g., potting media at 1200

ppm Hoagland solution), hydroponic protocols enhance biomass accumulation (Munda et al., 2025), confirming that closed-loop, controlled-environment agriculture offers a scalable, technically efficient, and economically viable model to mitigate urban land and water constraints in South Asia.

Integrated Closed-Loop Systems & Niche Production

Integrated closed-loop agro-technologies and controlled-environment agriculture (CEA)—encompassing aquaponics, hydroponics, and aeroponics—have emerged as vital paradigms for mitigating land constraints, severe water scarcity, and climate-driven food insecurity in resource-constrained contexts like India (Biswas et al., 2024; Sreejith et al., 2025). Scholarly evidence underscores the transformative potential of these soil-less systems across niche agricultural verticals, ranging from rapid 7- to-10-day hydroponic green fodder cultivation to alleviate livestock nutritional deficits (Shit, 2019) to nutrient-dense microgreen production leveraging controlled environments for accelerated market growth (Pradhan et al., 2025). Moreover, novel implementations such as ornamental fish-based aquaponics reinforce Sustainable Development Goal 2 (Zero Hunger) by harmonizing circular nutrient bio-conversion with urban economic opportunities supported by institutional schemes like the Pradhan Mantri Matsya Sampada Yojana (Verma et al., 2025). However, despite an accelerating global publication trajectory and proven biological efficiency (Sreejith et al., 2025), commercial-scale diffusion within India remains constrained by multidimensional barriers. Empirical multi-criteria evaluations reveal that while a deficiency in technical expertise represents the foremost effect-group bottleneck, underlying cause-group barriers such as high capital intensity, energy dependency, environmental instability, and complex pH management heavily inhibit widespread adoption (G. Kumar et al., 2023; Shit, 2019). Unlocking the full economic feasibility and operational scalability of these sustainable systems ultimately necessitates structured policy support, targeted financial frameworks, and multi-stakeholder knowledge dissemination strategies (Biswas et al., 2024; G. Kumar et al., 2023; Sreejith et al., 2025).

Urban Architecture, CEA & Spatial Hotspots

Recent literature underscores the transformative potential of Controlled Environment Agriculture (CEA), precision farming, and advanced spatial technologies in addressing urban food insecurity, climate vulnerability, and resource constraints, particularly within the Indian context. A synthesized body of research highlights that integrating hydroponics with Internet of Things (IoT), artificial intelligence (AI), and vertical farming can significantly enhance crop productivity by 25% to 50% while reducing land, water, fertilizer, and labor requirements (Chauhan & Kaur, 2025; Manimozhi & Krishnamoorthy,

2025; Maheshwari, 2021; Saraswat & Jain, 2021). Spatial analytic techniques, such as integrating vegetation indices with Getis–Ord G_i^* hotspot analysis on high-resolution satellite imagery, have proven highly effective for evidence-based spatial planning and crop monitoring during adverse conditions like monsoon flooding (S. Kumar & Parida, 2021). Furthermore, protected cultivation and modular farming frameworks emerge as vital strategies for land conservation, soil remediation, and building decentralized, climate-resilient local food systems (Mahmud et al., 2023; Sharma et al., 2021). However, high initial capital expenditure and the demand for specialized technical expertise remain critical implementation barriers (Maheshwari, 2021). To bridge these gaps, architectural integration and multidisciplinary collaborations (among architects, engineers, and agricultural experts) are increasingly essential for designing multifunctional urban spaces that drive community engagement, promote rural-urban economic resilience, and advance Sustainable Development Goal 2 (Zero Hunger) aligned with national initiatives like Viksit Bharat@2047 (Chauhan & Kaur, 2025; Nikam & Nikam, 2026; S. Kumar & Parida, 2021).

Adoption Barriers, LCA & Policy Economics

Recent scholarly discourse increasingly highlights Controlled Environment Agriculture (CEA) and hydroponic technologies as strategic interventions for mitigating climate stress and enhancing urban food security within India's broader development vision, such as Viksit Bharat@2047 (Chauhan & Kaur, 2025; Paturu & Varadarajan, 2024). Evaluating these systems through a Product-Service Systems lens and cradle-to-gate Life Cycle Assessment (LCA), empirical findings demonstrate that environmental efficacy varies significantly by operational structure; specifically, greenhouse hydroponic farming offers superior sustainability over indoor facilities, cabinet-selling models, and conventional soil-based methods by substantially reducing greenhouse gas emissions, fossil fuel consumption, and human toxicity impacts (Paturu & Varadarajan, 2024). Furthermore, extensive systematic and analytical literature reviews affirm that while automated CEA frameworks optimize resource use efficiency, yield optimization, and year-round productivity, their techno-economic feasibility and adoption trajectories are tightly bound to regional microclimates, capital intensity, and socio-economic constraints (Chauhan & Kaur, 2025; Sharma et al., 2024). Consequently, while contemporary research establishes a strong theoretical consensus regarding the transformative potential of urban hydroponics and CEA, scholars emphasize the pressing need for context-specific empirical investigations and tailored policy initiatives to overcome structural adoption barriers and quantify environmental trade-offs across diverse agricultural landscapes (Sharma et al., 2024).

Eco-Nanotechnology & Soil Reclamation

Anthropogenic disturbances and intensive resource extraction severely compromise pedological integrity, creating an urgent imperative for advanced soil reclamation and sustainable agricultural inputs. Assessing the baseline extent of mining-induced degradation, Saha et al. (2026) utilized an integrated geospatial and multivariate framework—incorporating satellite DEMs, SEM, and Principal Component Analysis—to evaluate edaphic deterioration in the Raniganj coalfield region, revealing severe spatial heterogeneity in fundamental soil parameters (pH ranging from 5.38 to 8.82, organic carbon from 0.31% to 0.99%, and available nitrogen from 182.0 to 508.06 kg/ha) and formulating a replicable Soil Quality Index (SQI) to guide targeted ecosystem restoration. To remediate such degraded agroecosystems while mitigating reliance on toxic agrochemicals, recent scholarship highlights the potential of natural bio-amendments and green nanotechnology. Investigating natural soil-derived organic matter, Singh et al. (2024) isolated humic acids (HAs) across five distinct land-use regimes in the Delhi-NCR region via IHSS, UV-Vis, and FT-IR protocols, discovering that forest-origin HA at an optimal dose of 1000 mg L⁻¹ (Treatment T3) significantly enhanced the physiological and biochemical performance of *Oryza sativa*. Parallely expanding eco-nanotechnology, Narula et al. (2025) synthesized biopolymer-supported chitosan silver and zinc oxide nanosheets using agricultural waste extracts from almond (*Prunus amygdalus*) husks and walnut (*Juglans regia*), demonstrating that green nano-priming substantially boosts seed germination kinetics and early vegetative vigor in *Vigna radiata*. Synthetically, these studies demonstrate that pairing high-resolution geospatial diagnostics of degraded soils (Saha et al., 2026) with targeted organic fractions (Singh et al., 2024) and green-synthesized biopolymer nanocomposites (Narula et al., 2025) provides a holistic, eco-friendly matrix for restoring soil quality and achieving sustainable crop productivity under increasing environmental stress.

Interpretation and Synthesis of Findings

The thematic analysis demonstrates that hydroponic farming should not be interpreted merely as an alternative method of crop cultivation; rather, it represents a broader technological transition towards resource-efficient, controlled, and knowledge-intensive agricultural systems. Across the reviewed literature, a consistent pattern emerges: hydroponics has significant potential to address land scarcity, water stress, urbanisation, climate uncertainty, and the growing demand for high-quality food. However, the findings also indicate that its contribution to sustainable agriculture is conditional rather than automatic. The sustainability performance of hydroponic systems depends on technological design, crop selection, energy sources, scale of operation, management capability, and the economic and institutional environment in which the technology is adopted.

Hydroponics as a Resource-Efficiency Strategy

The first major interpretation emerging from the literature is that hydroponics fundamentally alters the relationship between agricultural production and natural resource use. Conventional agriculture depends heavily on land quality, climatic conditions, and large quantities of water. In contrast, hydroponic production systems allow water, nutrients, and environmental conditions to be managed with greater precision. The reviewed studies consistently indicate improvements in water-use efficiency, land productivity, nutrient management, and crop intensity.

The evidence on vertical hydroponics and controlled cultivation particularly suggests that high-value crops can be produced intensively within limited physical spaces. Studies on lettuce and other leafy vegetables demonstrate that hydroponic systems can reduce crop duration, improve yield and quality, and substantially increase water-use efficiency compared with conventional cultivation. Thus, the principal sustainability advantage of hydroponics lies not simply in producing more food, but in increasing output per unit of critical resources.

This finding is especially important for countries such as India, where agricultural land is under pressure from urban expansion, fragmentation of holdings, industrial development, and environmental degradation. Hydroponics therefore has the potential to complement conventional agriculture by providing an alternative production system for locations where land and water constraints are particularly severe.

Digital Technologies Transform Hydroponics into Precision Agriculture

A second important finding is the increasing integration of hydroponics with digital technologies. The literature shows a transition from manually managed systems towards smart hydroponic platforms supported by the Internet of Things, sensors, cloud communication, automation, artificial intelligence, and machine-learning applications.

This technological convergence changes the nature of hydroponic farming. Rather than relying primarily on continuous human observation, smart systems can monitor variables such as nutrient concentration, pH, electrical conductivity, temperature, humidity, and water levels in real time. Automated decision-making can improve the precision of nutrient delivery and environmental management while reducing unnecessary resource losses.

The findings suggest that the future sustainability of hydroponics will increasingly depend on digital capability. Advanced monitoring and predictive systems can improve operational efficiency and reduce wastage; however, they may simultaneously increase technological complexity. Consequently, digitalisation creates both opportunities and new barriers. Farmers and entrepreneurs require technical knowledge, reliable electricity,

digital infrastructure, maintenance capacity, and financial resources to operate advanced systems successfully.

Therefore, technological sophistication should not be considered an end in itself. For the Indian context, the development of low-cost, energy-efficient, user-friendly, and locally adaptable smart hydroponic systems may be more important than the adoption of highly complex technologies.

Agronomic Performance Depends on System and Crop-Specific Optimisation

The third theme demonstrates that hydroponics cannot be treated as a uniform technology with identical outcomes across crops and locations. The reviewed experimental studies show that productivity and quality are influenced by the cultivation technique, nutrient concentration, growing medium, environmental conditions, and cultivar selection.

Comparative evidence from lettuce cultivation indicates that systems such as deep-water culture and nutrient film technique can generate different outcomes in terms of yield, water conservation, crop duration, nutritional quality, and economic returns. Similarly, cultivar-specific differences indicate that certain varieties may perform better under particular hydroponic environments.

These findings have an important implication for future research and policy. The promotion of hydroponics should move beyond general claims regarding its benefits and focus on the identification of optimal crop–technology–location combinations. Hydroponic farming may be particularly suitable for leafy vegetables, microgreens, high-value horticultural crops, fodder, and specialised urban food markets. Its sustainability and profitability, however, are likely to vary considerably across crops and production systems.

Thus, the evidence supports a context-specific approach rather than a universal model of hydroponic adoption.

Closed-Loop and Integrated Systems Strengthen Circularity

The literature on aquaponics, hydroponic fodder, ornamental fish-based systems, and other integrated production models reveals another important dimension of sustainability: circular resource utilisation. In these systems, the outputs or by-products of one production activity can become inputs for another.

Aquaponics is particularly significant because it integrates fish production and plant cultivation through nutrient recycling. Such systems have the potential to improve resource productivity by reducing waste and enabling the simultaneous production of multiple outputs. Similarly, hydroponic fodder systems can support livestock production in areas affected by land and water constraints.

The synthesis of these findings suggests that the greatest sustainability potential may emerge when hydroponics is embedded within broader circular food systems rather than operated as an isolated production technology. Future agricultural models could integrate hydroponics with aquaculture, renewable energy, urban waste management, protected cultivation, and local food distribution networks.

However, the literature also highlights important limitations. Integrated systems require specialised knowledge, careful nutrient management, stable environmental conditions, reliable power supply, and significant initial investment. Therefore, circularity alone does not guarantee scalability. Institutional support, training, and appropriate business models are necessary for wider adoption.

Hydroponics Can Contribute to Urban Food-System Transformation

The reviewed studies strongly associate hydroponics with urban agriculture, vertical farming, and controlled-environment production. This indicates that hydroponics has a particularly important role in regions where food demand is concentrated but cultivable land is limited.

Vertical and controlled-environment systems can bring food production closer to consumers. This may reduce dependence on distant production areas and potentially improve the availability of fresh produce. The literature on urban architecture, spatial analysis, and controlled-environment agriculture further suggests that hydroponics can be integrated into buildings, rooftops, institutional spaces, and other urban structures.

The broader interpretation is that hydroponics represents a shift from geographically dispersed agricultural production towards more spatially flexible food systems. Agriculture may increasingly become integrated with urban infrastructure, architecture, technology, and local supply chains.

For India, this creates opportunities for metropolitan regions and rapidly expanding secondary cities. However, urban hydroponics should not be viewed as a complete replacement for conventional agriculture. Instead, it is better understood as a complementary system capable of supplying selected crops, particularly perishable and high-value products, closer to centres of consumption.

Environmental Sustainability Involves Important Trade-Offs

One of the most significant findings of the thematic synthesis is that hydroponics cannot automatically be classified as environmentally sustainable. Although the technology can reduce land and water requirements, its environmental performance is influenced by energy consumption, infrastructure requirements, lighting, cooling, pumping, nutrient production, and the materials used in controlled-environment systems.

The life-cycle perspective presented in the reviewed literature demonstrates that different hydroponic production models may generate substantially different environmental outcomes. Greenhouse-based systems, for example, may perform differently from highly controlled indoor production systems because of variations in electricity and infrastructure requirements.

This finding challenges the assumption that technological agriculture is inherently sustainable. A reduction in water or land use may be accompanied by higher energy consumption or carbon emissions. Therefore, sustainability assessment should adopt a multidimensional framework that considers water, land, energy, greenhouse-gas emissions, waste generation, nutrient losses, economic viability, and social outcomes simultaneously.

The transition towards renewable energy and energy-efficient technologies may therefore be critical to improving the long-term environmental sustainability of hydroponic farming.

Economic and Institutional Barriers Remain the Major Constraints

Despite the technical potential identified across the literature, widespread adoption remains constrained by economic, technological, and institutional barriers. High initial investment, lack of technical expertise, unreliable electricity, limited awareness, maintenance requirements, and uncertain market access repeatedly emerge as important obstacles.

The analysis of adoption barriers in aquaponics is particularly relevant because it demonstrates that technological challenges are closely connected with financial and knowledge-related constraints. A technologically efficient system may still fail if farmers lack the necessary skills, access to finance, or institutional support.

The synthesis therefore suggests that the major challenge facing hydroponics in India is not simply technological availability but the creation of an enabling ecosystem. Adoption will require access to affordable credit, technical training, extension services, research support, market development, reliable energy, and appropriate policy incentives.

This also implies that hydroponics may initially develop more rapidly among commercial enterprises, start-ups, urban entrepreneurs, research institutions, and high-value crop producers. For wider inclusion of small and marginal farmers, low-cost and decentralised models must be developed.

Overall Synthesis

The findings collectively indicate that hydroponic farming has considerable potential to contribute to sustainable agricultural development, particularly through improved water and land productivity, controlled cultivation, year-round production, and technological

innovation. However, the evidence does not support the conclusion that hydroponics is universally superior to conventional agriculture.

Instead, the thematic synthesis suggests that hydroponics should be understood as a **context-dependent sustainability strategy**. Its advantages are likely to be strongest in situations characterized by water scarcity, limited land availability, urbanisation, climate vulnerability, demand for high-value crops, and access to technological and energy infrastructure.

The reviewed literature also reveals a transition in hydroponic research. Earlier studies primarily focused on crop production and technical feasibility, whereas more recent research increasingly incorporates artificial intelligence, IoT, vertical farming, controlled-environment agriculture, life-cycle assessment, circular production systems, spatial planning, and adoption economics. This indicates that hydroponics is evolving from a specialised cultivation technique into an interdisciplinary agricultural innovation system.

For India, the most promising pathway is unlikely to be the replacement of traditional agriculture. Rather, hydroponics should complement existing agricultural systems by addressing specific production challenges and serving particular markets. A sustainable transition will require locally adapted technologies, renewable-energy integration, crop-specific optimisation, capacity building, affordable financing, and policy support.

RECOMMENDATIONS

To operationalize hydroponic farming as a viable catalyst for sustainable agriculture in emerging economies like India, key policy, technological, and research interventions are recommended:

- **Targeted Policy & Financial Incentives:** Policymakers should establish dedicated subsidy schemes, concessional credit lines, and micro-loans to lower high initial capital barriers. Support should prioritize low-cost, greenhouse-based systems integrated with solar energy to reduce grid reliance and mitigate cradle-to-gate carbon emissions identified in life-cycle assessments.
- **Agronomic Standardization & Crop Calibration:** Agricultural extension agencies must develop region-specific operational protocols. Guidelines should systematically pair short-cycle, high-value crops (e.g., leafy greens, microgreens, fodder) with optimal system configurations—such as Nutrient Film Technique (NFT) or Deep Water Culture (DWC)—tailored to localized microclimates.
- **Capacity Building & Inclusive Technology:** Public-private partnerships should establish technical training centers to bridge critical knowledge deficits in water chemistry, pH control, and disease management. Promoting modular, low-cost

Internet of Things (IoT) and AI monitoring tools will enable smallholders to practice precision fertigation without prohibitive technology costs.

- **Promoting Circular Agro-Ecosystems:** Urban planning frameworks and agricultural schemes should incentivize circular systems, including aquaponics and building-integrated agriculture. Capitalizing on nutrient recycling and vertical spatial optimization will enhance urban food resilience and advance Sustainable Development Goals (SDG 2 and SDG 12).

CONCLUSION

This PRISMA-driven systematic synthesis demonstrates that hydroponic farming offers a viable pathway toward sustainable agriculture by drastically enhancing water-use efficiency, crop yields, and spatial productivity. Integrating digital technologies (IoT, AI) and closed-loop systems further amplifies resource circularity. However, hydroponics is not a universal replacement for conventional farming; its contribution to sustainability is conditional on mitigating key trade-offs, including high initial capital expenditure, energy intensity, and technical adoption barriers in developing agrarian economies like India. Ultimately, strategic policy support, localized low-cost technological adaptations, and targeted infrastructure are essential to positioning hydroponics as a complementary driver of long-term food security.

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