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Enhancing Food Safety in Bangladesh: Exploring Hydroponic Farming as a Sustainable Solution

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ABSTRACT

Food safety in Bangladesh is critically threatened by heavy metal and pesticide contamination from conventional agriculture. This review aims to evaluate hydroponic farming as a viable and sustainable solution to mitigate these food safety risks by analyzing its benefits, challenges, and resource efficiency compared to soil-based methods. While the food safety crisis in Bangladesh and the general benefits of hydroponics have been studied, there is a critical research gap in the comprehensive evaluation of hydroponics specifically as a solution to the nation's unique contamination and adoption challenges. A systematic literature survey was conducted using academic databases and institutional websites. The literature confirms that conventional farming results in significant heavy metal (As, Cd, Pb) and pesticide residues in produce, often exceeding international safety limits. Key findings show that hydroponic systems virtually eliminate soil-borne contamination and drastically reduce pesticide dependency. Furthermore, hydroponics demonstrates superior resource efficiency, using up to 90% less water and significantly less space while increasing yield. Key challenges include high initial investment costs, technical knowledge gaps, and the need for climate-resilient infrastructure. Hydroponic farming presents a robust solution to the food safety crisis by producing cleaner, safer food. Widespread adoption requires strategic policy interventions, including financial incentives, robust farmer training programs, and research into cost-effective, climate-resilient systems. Integrating hydroponics can significantly enhance national food security and public health.

INTRODUCTION

The Food Safety Crisis in Bangladesh

Food safety is a critical public health and economic concern in Bangladesh. Despite achieving self-sufficiency in food production, the quality and safety of that food are frequently compromised by widespread contamination from pesticides, heavy metals, and microbial hazards. The excessive application of chemical fertilizers and pesticides, coupled with the use of polluted irrigation water, poses a continuous threat. Studies consistently indicate that pesticide residues in Bangladeshi food products, such as vegetables and fish, often exceed maximum permissible international safety standards (Ferdous *et al.*, 2021; Sarker *et al.*, 2021), leading to significant public health risks.

Furthermore, heavy metal contamination is pervasive. Arsenic (As), cadmium (Cd), chromium (Cr), and lead (Pb) have been detected at alarming levels in staple crops, vegetables, and fish (Proshad *et al.*, 2020; Real *et al.*, 2017). These contaminants primarily originate from untreated industrial effluents and the composition of chemical fertilizers, which pollute agricultural soil and water sources (Ahmed *et al.*, 2019; Hezbullah *et al.*, 2016). This situation underscores the urgent need for sustainable agricultural practices that can maintain high-yield production while ensuring food safety.

Limitations of Conventional and Organic Farming

Traditional soil-based farming practices are a major contributor to the food safety problem and broader environmental degradation. These methods often lead to declining soil fertility, soil erosion, biodiversity loss, and significant water pollution (AlShrouf, 2017). The heavy reliance on chemical inputs not only introduces contaminants into the food chain but also depletes natural resources, creating a cycle of environmental harm and public health risk.

While organic farming has been proposed as a sustainable alternative that reduces reliance on synthetic inputs (Ferdous *et al.*, 2021), its large-scale adoption in Bangladesh has been limited. This is primarily because organic farming requires a fundamental shift in farming practices and faces challenges in achieving the same scale and yield as conventional methods, which farmers are hesitant to adopt without significant support and proven profitability (Fuad & Matsui, 2025). With food quality remaining poor and contributing to nutritional imbalances (Sela Saldinger *et al.*, 2023), innovative solutions are necessary.

Hydroponics as a Proposed Solution

Hydroponic farming, a soilless cultivation method, presents a promising solution to these interconnected challenges. By eliminating soil, it directly addresses the primary pathway for heavy metal and soil-borne pathogen contamination. This controlled environment minimizes the need for pesticides and allows for the precise delivery of nutrients, optimizing plant growth and resource use.

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Studies demonstrate that hydroponic systems can achieve up to 90% greater water efficiency compared to traditional farming and significantly increase productivity per unit area (AlShrouf, 2017; Barbosa *et al.*, 2015; Monsees *et al.*, 2019). Countries such as the Netherlands, Singapore, and India have successfully integrated hydroponics into their agricultural sectors, demonstrating its potential for high-yield, resource-efficient, and safe food production (Kumar *et al.*, 2023; Martin & Molin, 2019). In Bangladesh, hydroponics particularly urban and vertical farms could revolutionize food production by providing safer crops, reducing reliance on contaminated land, and enhancing food security in densely populated cities (Azad *et al.*, 2016; Safayet *et al.*, 2017).

Research Gap and Objectives

Despite its potential, the widespread adoption of hydroponics in Bangladesh is hindered by significant challenges, including high initial investment costs, limited technical awareness, policy gaps, and technological constraints (Ghose *et al.*, 2014; Uddin & Dhar, 2018). While many studies have highlighted the food safety crisis in Bangladesh and others have discussed the general benefits of hydroponics, there is a lack of comprehensive analysis that critically evaluates hydroponics specifically as a solution to Bangladesh's unique food safety challenges. This review aims to fill this gap by exploring the food safety challenges in Bangladesh and evaluating hydroponic farming as a viable and sustainable solution. By synthesizing data on contamination levels, resource efficiency, and global success stories (Angeloni & Pontetti, 2020; Sambo *et al.*, 2019), this study proposes strategic policy recommendations to facilitate the adoption of hydroponics, aiming to ensure a safer and more sustainable food system for the nation.

MATERIALS AND METHODS

This study is based on a systematic literature survey of published research articles, reports, and conference proceedings related to hydroponic farming, food safety, and sustainable agriculture in Bangladesh.

Literature Search Strategy

A comprehensive search was conducted using online academic databases, including Google Scholar, PubMed, ScienceDirect, Scopus, Springer, and ResearchGate, as well as institutional and governmental websites. The search strategy employed a combination of targeted keywords to gather contemporary and credible information. The selected keywords included: "Hydroponic farming in Bangladesh," "Food safety in hydroponics," "Sustainability of soilless agriculture," "Pesticide-free farming methods," "Nutrient management in hydroponics," "Heavy metal contamination in conventional farming," and "Comparing hydroponic and traditional farming systems".

Selection Criteria and Data Synthesis

The selection of literature was guided by the following criteria:

Inclusion Criteria: Studies were included if they (1) discussed food safety issues (pesticide or heavy metal contamination) in Bangladesh; (2) analyzed hydroponic systems (e.g., Nutrient Film Technique, Deep Water Culture) in terms of food safety, yield, or resource efficiency; (3) provided comparative data between hydroponic and conventional farming; or (4) presented case studies or policy analyses relevant to agricultural technology adoption in developing countries.

Exclusion Criteria: Studies were excluded if they were not published in English, were not peer-reviewed (unless they were significant government or institutional reports), or focused on agricultural topics not relevant to hydroponics or food safety.

While a formal PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology was not employed, a careful screening process was conducted to ensure the quality of the collected data and to avoid redundancies. The gathered information was analyzed using a qualitative-thematic approach. Data was extracted and summarized to focus on three key thematic areas: (1) the benefits of hydroponics for mitigating heavy metal and pesticide contamination; (2) the comparative environmental sustainability and resource efficiency of hydroponics; and (3) the challenges and limitations to scaling up hydroponic farming in Bangladesh. This synthesis was used to identify research gaps and formulate actionable recommendations.

RESULTS AND DISCUSSION

Current state of agriculture and food safety in Bangladesh

Bangladesh has achieved self-sufficiency in food production. However, frequent population growth, land degradation, and scarcity remain significant food security concerns (Ghose *et al.*, 2014; Islam, 2022; Sikder & Islam, 2023). Pesticide use is one of the biggest challenges in modern agriculture. Pesticides spread throughout the foodstuffs are a major concern due to the weak regulatory systems, absence of awareness on the farmer's part, and improper handling processes (Sarker *et al.*, 2021). Therefore, pesticide residue levels in most food products in Bangladesh exceed international standards and guidelines, with pesticides being a source of heavy metals, posing a significant health threat to consumers (Ferdous *et al.*, 2021).

Pesticide contamination in food crops is not the only source of heavy metal contamination in food crops. Studies have shown arsenic (As), cadmium (Cd), chromium (Cr), and lead (Pb) as major contaminants of vegetables, rice, and fish with variably high metal concentrations over different rice growing regions (Proshad *et al.*, 2020; Real *et al.*, 2017). Industrial effluents, chemical fertilizers, and pesticides are major sources of these heavy metals, and they have contaminated agricultural soil and water (Ahmed *et al.*, 2019; Hezbullah *et al.*, 2016). In addition, the use of heavy metal-contaminated dust to irrigate the crops from industrial zones aggravates this problem, especially during the dry season when the concentration level of heavy metals in the water sources is greater, resulting in the accumulation of heavy metals in vegetables (Ahmed *et al.*, 2019). To illustrate the severity of contamination, Table 1 presents the levels of heavy metal accumulation in root vegetables commonly consumed in Bangladesh. The data emphasize the urgent need for alternative farming methods that eliminate soil exposure to heavy metals.

Table 1: Heavy Metal Contamination in Root Vegetables

Heavy Metals	Root Vegetables	Range in Different Phase (mg/kg dw)	Mean (mg/kg dw)	Maximum Permissible Limit (MPL) (mg/kg dw) (FAO/WHO 2011)
Chromium (Cr)	Beet	0.60 - 1.90	1.20	2.30
	Radish	0.80 - 2.10	1.53	2.30
	Carrot	0.50 - 1.90	1.58	2.30
	Turnip	0.80 - 49.60	13.50	2.30
Cadmium (Cd)	Beet	0.10 - 0.40	0.20	0.20
	Radish	0.00 - 0.30	0.23	0.20
	Carrot	0.00 - 0.50	0.30	0.20
	Turnip	0.00	0.00	0.20
Lead (Pb)	Beet	0.00	0.00	0.30
	Radish	0.00	0.00	0.30
	Carrot	0.00 - 3.00	0.75	0.30
	Turnip	0.00	0.00	0.30
Nickel (Ni)	Beet	0.00	0.00	2.70
	Radish	0.00 - 3.30	2.58	2.70
	Carrot	0.00	0.00	2.70
	Turnip	0.00 - 1.10	0.28	2.70
Copper (Cu)	Beet	11.40 - 19.30	13.90	10.00
	Radish	2.00 - 9.50	6.78	10.00
	Carrot	2.80 - 4.20	3.68	10.00

Source: Islam et al. (2018).

Organic farming has been proposed as an alternative to conventional agriculture, reducing reliance on synthetic fertilizers and pesticides. This minimizes the introduction of heavy metals into the soil, which are often present as contaminants in chemical substances. This sustainable approach reduces the accumulation of heavy metals in crops, promoting safer and healthier food production. The scale-up of adoption of organic farming in Bangladesh has been limited because of the need for a fundamental change in farming practices and the adoption of organic farming practices by farmers (Roy *et al.*, 2019). Though food availability and access have improved, the quality of food is still poor and causes nutritional imbalances as well as malnutrition among a vast majority of the population (Sela Saldinger *et al.*, 2023).

The ongoing solution to this problem shows the need for fresh, innovative solutions to better food safety and better-quality nutrition, like hydroponic farming.

Hydroponic farming as a solution

Hydroponic farming eliminates soil contamination, reduces pesticide dependence, and optimizes nutrient absorption. Research shows hydroponic systems use up to 90% less water than traditional farming while improving productivity per unit area (AlShrouf, 2017; Barbosa *et al.*, 2015; Monsees *et al.*, 2019). Crops grown hydroponically have significantly lower chemical residues, ensuring safer food production. Countries like the Netherlands, Singapore, and India have successfully adopted hydroponics, demonstrating its potential for sustainable agriculture. (For further discussion on food safety and environmental benefits, see sections 3.3 and 3.4)

Hydroponic systems reduce pesticide usage and lessen common issues associated with soil-based farming, such as bacterial contamination. By eliminating soil as a growing medium, hydroponics reduces the risk of soil-borne pests and pathogens, creating a cleaner and more controlled environment for plants. Additionally, the precision in nutrient delivery minimizes waste and promotes healthier plant growth, further reducing the need for chemical interventions. This sustainable approach not only improves crop quality but also aligns with eco-friendly agricultural practices (AlShrouf, 2017; Barbosa *et al.*, 2015; Monsees *et al.*, 2019; Sela Saldinger *et al.*, 2023).

Furthermore, hydroponic farming optimizes resource efficiency. Hydroponic farming requires significantly less water and fewer fertilizers, leading to reduced environmental impact from chemical use (AlShrouf, 2017; Monsees *et al.*, 2019). Further, in cities, vertical hydroponic systems actually enhance this efficiency even more. By optimally using space, vertical farming can eliminate enormous transportation requirements and thereby lower production costs and reducing greenhouse gas emissions and resource depletion (Martin & Molin, 2019).

By integrating smart farming technologies and the Internet of Things into the hydroponic system, enhancing overall system efficiency. These systems based on real time data and automation help in maximizing nutrient delivery, monitoring environmental conditions, and predicting possible issues; hence, hydroponic farming can be a sustainable, viable approach to solving modern agricultural challenges (Angeloni & Pontetti, 2020).

Hydroponic farming and food safety

Hydroponic farming presents a promising solution to Bangladesh's food safety challenges, particularly in addressing heavy metal contamination and pesticide residues. Arsenic, cadmium, and lead are among the most prevalent contaminants, primarily due to industrial effluents polluting agricultural soil and irrigation water. These contaminants have severely impacted traditional farming systems. While heavy metals can persist in the food chain, hydroponic farming significantly reduces this risk by utilizing purified water and controlled nutrient solution (Nahar *et al.*, 2020).

A hydroponic system provides a controlled environment where plant growth conditions are precisely managed, reducing the need for chemical interventions. With reduced exposure to common pests and soil-borne diseases, there is less need for pesticides, resulting in cleaner produce that is safer for consumers concerned about chemical contamination (Nahar *et al.*, 2020).

As discussed earlier in the section 3.2, hydroponic farming significantly reduces contamination risks and pesticide use, ensuring safer food production. This is further illustrated in Figure 1, which compares heavy metal contamination levels in hydroponic and conventional farming systems in Bangladesh. The data show a notable reduction in arsenic, lead, and cadmium in hydroponically grown vegetables, reinforcing the effectiveness of soil-free cultivation in eliminating toxic accumulation. The values for hydroponics in the chart are based on controlled conditions documented in global research, representing the potential for eliminating toxic accumulation. This comparison underscores the effectiveness of soilless cultivation in breaking the cycle of contamination prevalent in Bangladesh's conventional agriculture (Dela Cruz *et al.*, 2022).

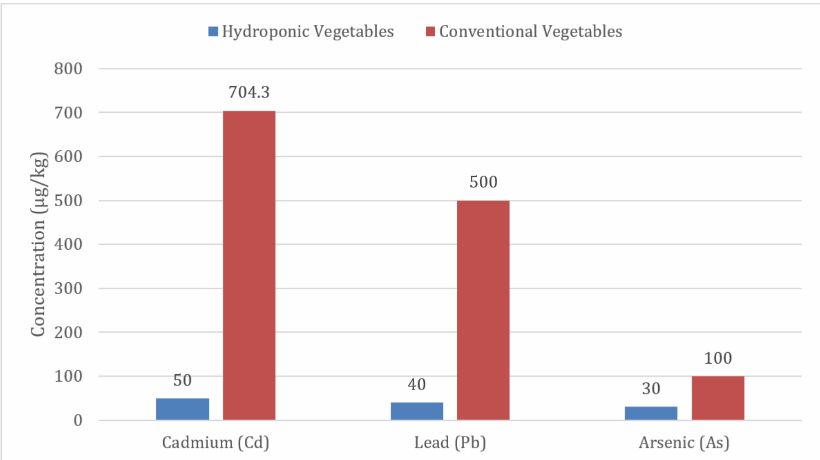

Figure 1: Heavy Metal Contamination Levels in Hydroponic and Conventional Vegetables. Comparison of contamination levels in Bangladesh, illustrating the reduction of arsenic, lead, and cadmium in hydroponic systems. *Source: (Shaheen et al., 2016; Masud & Bhowmik, 2018).*

The reach of heavy metal contamination (Cadmium, Lead, and Arsenic) in hydroponically and conventionally grown vegetables is both compared graphically in Bangladesh. It allows clean visualization of the real extent of contamination in the two farming methods endured. Therefore, this comparison is particularly relevant in Bangladesh, where contamination of agricultural products with heavy metals has grown due to industrial pollution and the use of contaminated irrigation water in conventional farming (Ahmed *et al.*, 2019).

Information on heavy metal contamination in hydroponic systems in Bangladesh is lacking. However, extensive research has been done on conventional farming, where vegetables are contaminated to extreme levels by factory pollution, wastewater irrigation, and soil contamination.

This is why the hydroponic vegetable contamination values presented in this bar chart are hypothetical controlled conditions that typify what the hydroponic system would look like from worldwide research.

Environmental sustainability of hydroponic farming

In regions like Bangladesh, where natural resources are limited, it is imperative to look for sustainable alternatives. Hydroponic farming offers a promising solution by conserving resources and providing an eco-friendly alternative to conventional farming practices. Unlike traditional farming, hydroponic systems eliminate the need for large-scale machinery, such as tractors for plowing, and significantly reduce greenhouse gas emissions. By minimizing the environmental impact of food production, hydroponic farming presents a more sustainable approach to agriculture (Karlowsky *et al.*, 2021).

Additionally, hydroponic systems can be integrated with renewable energy sources, such as solar power, further reducing the carbon footprint associated with conventional farming. The combination of hydroponic and hydro-organic farming practices, along with the use of renewable energy, can enhance sustainability and contribute to a more environmentally friendly agricultural system (Karlowsky *et al.*, 2021; Masud & Bhowmik, 2018).

Another advantage of hydroponics is its water usage, as its efficiency is one of the highest among known growing systems. Hydroponics is still even more water efficient than any conventional methods of farming and is an idea that can feed a country that is constantly misusing water (Nahar *et al.*, 2020).

Closed-loop hydroponic systems of similar design also add up to their environmental benefits. For the same reason, they are cheaper and not as bad for the environment because they do not waste water and nutrients in the way a traditional system would. For example, hydroponic is combined with aquaponic, which means fish waste as organic manure to plants minutely. The integration presented here also gives a circular, sustainable view of how resources are optimally utilized while environmental pollutive impacts are vigorously curbed (Goddek *et al.*, 2019).

Hydroponic farming supports environmental sustainability by conserving water, reducing reliance on chemical pesticides, and minimizing soil degradation. These advantages contribute to a lower environmental footprint and align with global efforts to promote sustainable agriculture.

Comparing yields, water and space uses: traditional farming vs. Hydroponic farming

The agriculture sector of Bangladesh also suffers from many problems that make it difficult to sustain its longevity and produce food for a sufficient population; some of them are water crises, eroding soil, high usage of pesticides, and unstable production. Conventional agriculture, which can be referred to as conventional farming, has been the most practiced method in the Bangladeshi agricultural system. But it has become really inefficient at present times throughout the growing climate change, even affecting the weather conditions and demanding unwise practices. Due to irrigation, chemical pesticide use, and fertilizers in conventional farming, environmental degradation arises through soil erosion, water pollution, and biodiversity loss (AlShrouf, 2017). Additionally, the decline in nutrient content, soil nutrient depletion, and imbalances are the causes of declining crop yields and low food production efficiency (Tan *et al.*, 2005). Conventional farming methods are highly inefficient, contributing to soil degradation, water pollution, and low resource utilization efficiency. Figure 2 illustrates the efficiency differences between hydroponic and conventional farming across key parameters, including nutrient absorption, yield efficiency, water usage, space utilization, pesticide dependency, and overall food safety.

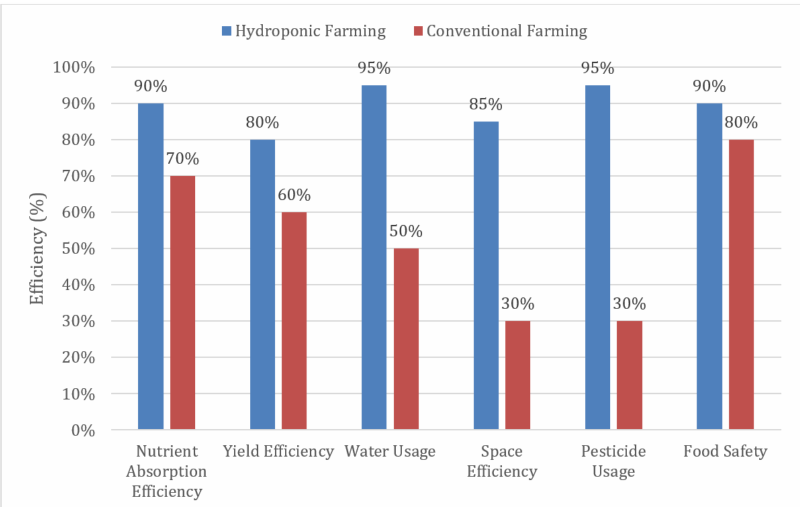

Figure 2: Comparison of Hydroponic vs. Conventional Farming Efficiency in Bangladesh. Evaluates differences in nutrient absorption, yield efficiency, and pesticide dependency between hydroponic and traditional farming.
Source: Azad et al. (2016).

The data indicates that hydroponic farming demonstrates superior efficiency in all assessed categories, particularly in resource utilization and sustainability. The significant differences in water and space efficiency, along with reduced pesticide dependency, underscore the potential of hydroponic farming as a viable alternative to conventional agricultural practices. These findings suggest that hydroponics could contribute to enhanced agricultural productivity and environmental sustainability in Bangladesh.

Transforming urban rooftops into green, sustainable food sources with hydroponics

Hydroponic farming on rooftops can be used as an innovation and a viable solution to improve food security in megacities such as Dhaka. Rooftop farming may greatly help address sustainability issues in cities by enhancing the quality of the air as well as lessening carbon emissions. It also helps decrease charging on stormwater management systems since the green structure assists in balancing rainwater (Safayet *et al.*, 2017).

Limited land is available in Dhaka and other major cities in Bangladesh; thus, hydroponic systems can play an important role within the urban structures. Vertical hydroponic farming is specifically efficient in areas concerning space management, as many types of crops may be grown in a small area. This approach would also assist in ensuring that the people within the urban areas have access to fresh produce and, at the same time, there is decreased reliance on transportation of the produce from other parts of the country, which would also assist in decreasing the carbon figure (Azad *et al.*, 2016; Safayet *et al.*, 2017). Current trends in commercial urban farming cover not only hydroponically based but raised beds and soil-based systems as well.

Although rooftop gardening can potentially enhance food production and consequently enhance the nutrition supply in Dhaka, long-term success requires policy support. Such policies may include giving subsidies to building owners, subsidizing hydroponic equipment, or even introducing sustainable urban agricultural practices, for instance, through seminars and workshops (Shariful Islam, 2004).

From a broad perspective, hydroponics as sustainable rooftop farming in urban areas is definitely a viable solution to food insecurity, mainly in densely populated centers. It promotes urban food resilience and an ecologically renewed local food production system.

Case studies and global examples

Hydroponic farming has attracted attention all over the world for its efficiency in increasing the productivity of food production as compared to traditional soil-based farming due to its characteristics that include scarcity of land, shortage of water, and an unfavorable environment for farming. A number of countries already use the hydroponic system, and, therefore, many of them are experiencing high yield rates, which is helpful in understanding the situation of Bangladesh.

Hydroponics is a modern and efficient method of growing food crops, and the Netherlands, one of the pioneers in hydroponic farming practices, has used large floor area hydroponic greenhouses to get high yields without high costs to the environment. These systems apply efficient water recycling practices; hence, the practice is up to 90% more effective than the conventional agricultural systems. This efficiency is very important, especially in its relationship to water supply and demand, which is a problem experienced in various nations worldwide, such as Bangladesh (Sharma *et al.*, 2018).

Due to the limited arable land in Singapore, the country has increasingly adopted hydroponic farming, particularly vertical farming. At the Sky Greens farm, a vertical hydroponic system is utilized, where crops are grown in stacked layers within a controlled climate throughout the year (Benke & Tomkins, 2017). This approach demonstrates the potential of hydroponic farming as a sustainable solution for densely populated urban areas like those in Bangladesh, where land scarcity and high population pressure are significant challenges.

Hydroponic farming has been embraced in India as a way of checking food shortages and degrading soil quality. Functioning with hydroponic techniques like the Kratky technique, Wick technique, and Deep Flow Technique (DFT) in detail, it focuses on a better farming system in areas where problems of the groundwater table and soil erosion are common. This system not only lowered the reliance on soil but also on water; hence, they are considered eco-friendly practices as compared to conventional agriculture (Kumar *et al.*, 2023).

Sweden, in general, has also studied the environmental effects of high-rising hydroponic farming systems, especially in Stockholm. A life cycle assessment study revealed that the sustainability of vertical farming could be greatly enhanced when plastic pots are replaced with paper ones and coir instead of traditional growing media. This study indicates that such practices might lower the total ecological impact of hydroponic systems and give important insights for enhancing sustainability in Bangladesh (Martin & Molin, 2019).

In the USA, work done on hydroponic lettuce in Yuma, Arizona, was done in contrast with land, water, energy usage of hydroponics, and traditional agriculture. When comparing hydroponic systems, higher yields were obtained, though the energy intensity was also higher, and this shows that areas with abundant renewable energy are ideal for hydroponic farming (Barbosa *et al.*, 2015). This finding is especially useful for the Bangladeshi context because energy accessibility and sustainability remain an issue of increasing concern.

Last but not least, Bangladesh has a moderate opportunity in hydroponic farming, especially the production of vegetables comprising tomato, lettuce, spinach, and capsicum. Hydroponic systems are capable of using only 10% of the water used in traditional farming and have shorter cycle times. Furthermore, it is also feasible to

grow hydroponic onions using groundwater; therefore, it provides a sustainable source of local vegetable production without much reliance on commercial fertilizer (AlShrouf, 2017; Khatun *et al.*, 2021).
This paper describes global examples and case studies depicting its utility and environmental advantages in hydroponic farming. Therefore, it forms a platform from which to advance its use in Bangladesh, which could go a long way in improving food security and sustainability.

Challenges and limitations of hydroponic farming in Bangladesh

Although research highlights the significance of hydroponic farming for food security and environmental sustainability in Bangladesh, several challenges and limitations must be addressed for its widespread adoption. One of the factors limiting hydroponic farming adoption is the high initial cost of setup and installation. High initial capital investment in hydroponic farm equipment, structures, and technology remains a major challenge since they are expensive to obtain by smallholder farmers or those from low-income backgrounds. Sustaining it from the grassroots is a challenge as it requires high initial investment costs to get started, leaving many who would benefit from this type of farming method behind (Karlowsky *et al.*, 2021; Uddin & Dhar, 2018).
Temperature control is a critical factor in hydroponic farming, and Bangladesh's hot and humid climate presents challenges that require careful monitoring. These are certain unfavorable factors that can easily affect crops in this country due to its extremely high temperature and high humidity levels. To avoid this, it is necessary to monitor and control the growing environment, which may consume time, be expensive, and not be possible for most farmers with limited access to technology and systems (Uddin & Dhar, 2018).
Another factor that is not easy to manage in hydroponic farming is nutrients. The nutrient concentration in the solution should be precisely controlled so as to favor plant growth. However, challenges such as nutrient solubilization, precipitation, and conflict amongst nutrients cause imbalances and nutrient disorders in crops. For these factors, complex instruments like multi-element sensors and machine learning algorithms are necessary to continuously control the nutrient concentration in the process line. Unfortunately, such tools are not easily accessible or inexpensive for the many farmers found in Bangladesh (Sambo *et al.*, 2019).
Additionally, hydroponic farming lacks training and extension services when adopted. However, most farmers lack awareness and knowledge about hydroponic systems, limiting their proper use. As a result, we are forced to set up organized training programs and extension services to create capacity and inculcate a new understanding of hydroponics needs and its benefits and applications (Uddin & Dhar, 2018).
While supporting the practice of hydroponic farming, certain environmental requirements for its success are dependent upon a stable sociopolitical environment. But the environment for additional profitable ventures (like hydroponic farming) in Bangladesh is not hospitable at the moment. Hydroponic feasibility and long-term sustainability in Bangladesh can have a real impact on land, water rights, and social equality. Nevertheless, hydroponics would not be successful without discussion of the broader social and political factors (Uddin & Dhar, 2018).
Addressing these challenges requires targeted policy interventions, improved infrastructure, and capacity-building programs. The next section outlines key recommendations to make hydroponic farming viable in Bangladesh.

Recommendation for future development

To ensure the successful integration of hydroponic farming into Bangladesh's agricultural landscape, several critical areas need further development:

Affordable and scalable technology

The major drawback for smallholder farmers remains the high installation cost of hydroponic systems. Subsidies, low-cost materials, and local manufacturing are ongoing efforts to make hydroponics more affordable and accessible. Modular and scalable systems also hold potential for gradual adoption, enabling small-scale farmers to integrate innovations over time (Ghose *et al.*, 2014).

Climate-resilient systems

The high humidity and fluctuating temperatures of Bangladesh are limiting hydroponic farming. While monitoring and controlled environments can mitigate the challenges of Bangladesh's hot climate, further research into climate-resilient hydroponic systems is essential for long-term sustainability. This could mean growing greener hydroponic crops in temperature-regulated greenhouses, solar-powered systems, or both to ensure the use of hydroponics everywhere. Investments in adaptable and resilient agricultural systems have been studied as key not only to reducing risks engendered by an uncertain beginning of Bangladesh's new climate regime but also to protect its food security under induced change in climate (Ferdous *et al.*, 2021; Islam, 2022).

Advanced nutrient management solutions

Good nutrient management is necessary for success in hydroponic farming. Future development efforts need to include the development of affordable, user-friendly nutrient management tools. Industrial machine learning and real-time sensors to optimize nutrient levels of crops could improve their health and decrease wastage. However, given the inefficiencies in nutrient utilization in Bangladesh agriculture, such systems face a need for research into increasing the productivity and sustainability of hydroponics (Ali *et al.*, 2025; Sarker *et al.*, 2021).

Training and extension services

To bridge the hydroponics knowledge gap, systemic training programs should be initiated to catch students on their knowledge of hydroponics. For instance, they could include system setup, nutrient management, and pest control. Collaborations with agricultural universities and NGOs could be leveraged to enable hydroponics to be utilized to get farmers trained comprehensively so that they can use hydroponics successfully. That is consistent with ongoing efforts to improve agricultural education and extension services in Bangladesh, and in fact, impacts on agricultural practice with the adoption of innovative farming practices have been demonstrated (Islam, 2022).

Policy support and infrastructure development

The schemes or policies are capable of assisting the governments to support hydroponic farming. Incentive measures to encourage the take-up of hydroponics included tax exemptions on hydroponically produced crops, grants for erecting structures for hydroponics, and affordable credit facilities for the development of hydroponics. In addition, the construction of cold storage systems and transport facilities will help reduce post-harvest losses and foster the establishment of hydroponics. The policymakers have highlighted these wastes for the food security of Bangladesh because of increasing pressure to make the food production process sustainable and less susceptible (Ferdous *et al.*, 2021).

Public awareness and consumer acceptance

Citizens may be reluctant to consume crops raised under the hydroponics farming system; however, informing them of the gains they got under the process is correct, including minimal use of pesticides and eco-friendly procedures. Market demand can also be brought about by conducting publicity campaigns about the health perception of foods grown in hydroponic systems. This would be in line with directions in Bangladesh that are geared towards increasing consumer confidence in safe food production practices, particularly organic farming (Ghose *et al.*, 2014).

Integration with renewable energy

Hydroponics may increase sustainability by integrating solar or wind energy production that has shorter operational costs and enhancing the sustainability coefficient of hydroponics. This is more so given Bangladesh's enormous emission reduction plans through the adoption of renewable power, as stated in the latest sustainability reports. However, It is mentioned that the use of renewable energy improves hydroponics and also increases the energy advantage along with the environmental impact for the agricultural portion of Bangladesh (Ghose *et al.*, 2014).

If these areas could be developed, then hydroponic farming could be an important solution to food and environmental safety, as well as the protection and advancement of food safety in Bangladesh's agriculture sector.

CONCLUSION

This review confirms that hydroponic farming presents a promising and viable solution to the critical food safety challenges in Bangladesh, which are largely driven by heavy metal and pesticide contamination from conventional, soil-based agriculture. The findings highlight that the primary advantages of hydroponic systems lie in their controlled, soilless environment, which minimizes exposure to contaminants, reduces pesticide dependency, and allows for year-round production. However, widespread adoption is currently hindered by significant limitations, most notably the high initial investment costs, the technical expertise required for nutrient and climate management, and the lack of supportive infrastructure. To overcome these challenges and harness the full potential of hydroponics, a multi-pronged strategy is essential. Future development must focus on optimizing nutrient formulations tailored to Bangladesh's specific agricultural needs and, crucially, on developing and promoting cost-effective, scalable systems accessible to small-scale farmers. Integrating these systems with renewable energy sources is vital for long-term environmental and economic sustainability. Ultimately, the successful adoption of hydroponic farming will depend on robust support from government policies, targeted private sector investment, and comprehensive farmer training programs. If these measures are implemented, hydroponics can significantly improve national food security, reduce public health risks, and create a more sustainable agricultural future for Bangladesh.

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