Is Aquaponics a Viable Alternative to Combat the Nutrition Crisis in India?

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***Abstract*—A study published by scientists at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), the International Food Policy Research Institute (IFPRI), and the Center for Economic and Social Studies (CESS) highlight that nutritional and protein deficiencies are major public health challenges in India. Approximately 60% to 73% of the Indian population suffers from protein deficiency, and traditional diets frequently lack essential micronutrients like fibre, vitamin B12, and iron. This statistic is alarming as it translates into lost labour productivity, skyrocketing healthcare costs, and premature mortality. Chronic illness and malnutrition directly reduce a workforce's physical and cognitive capacity, shifting national resources away from growth and development and into reactive medical spending. Aquaponics can significantly help resolve India's nutritional challenges by providing a consistent, hyper-local supply of both protein (fish) and micronutrients (fresh produce). While it cannot replace traditional staple crops like wheat or rice, it is a highly effective, space-saving tool for combating malnutrition in the country. This paper analyses its advantages and challenges in large scale adoption.**

***Index Terms*—Aquaponics, Nutrition, malnutrition, protein, vitamins, iron, health crisis, diet, healthcare, IOT based monitoring, food security, bio-integrated agriculture, fish-plant symbiosis**

I. INTRODUCTION

Poor nutrition is undoubtedly one of India's most critical public health challenges, manifesting as a severe "double burden": persistent undernutrition coexisting with a rapidly rising tide of obesity, micronutrient deficiencies, and diet-related non-communicable diseases. According to the 2025 Global Hunger Index, India ranks 102nd out of 123 countries with sufficient data to calculate 2025 GHI scores. With a score of 25.8 in the 2025 Global Hunger Index, India has a level of hunger that is serious (1). India also has the highest child wasting rate in the world at 18.7%. And 35.5% of children under five are medically listed as having their growth stunted, a condition that leads to long-term developmental complications. According to the World Bank, over 389 million people in South Asia live in poverty, with India accounting for nearly 40% of the global poverty rate at the $3.65 per day poverty line (2, 3). This economic hardship is a root cause of malnutrition, leaving 62 million children 48% of India's child population living with weak immune systems, higher disease risk, and impaired cognitive development, according to data from the Population Reference Bureau. Malnutrition among under-five children is a major public health problem in India. This is reflected by the fact that the prevalence of under-weight children in India is among the highest in the world and is nearly double that of Sub-Saharan Africa (4). Good nutrition is essential for a child's physical growth, brain development, and learning ability. Malnutrition in early life does more than affect body weight; it permanently impairs cognitive development. Poor nutrition during the first 1,000 days can cause irreversible damage, leading to poor school performance and reduced social and economic productivity in adulthood (5). Malnutrition in India is a serious and pervasive problem, despite that nation's recent decades of economic growth. With one of the highest rates of food disparity in the world, nearly half of India's children are considered underweight or malnourished by international standards. This issue is both urgent and widespread, significantly impacting India's people and its future by limiting the physical, cognitive, and economic potential of its next generations (6,7).

Malnutrition in Indian teenagers is no less challenging. It is found to be characterized by a "double burden", where severe undernutrition (stunting and thinness)

coexists with a rapid rise in overnutrition (overweight and obesity). According to data from the Comprehensive National Nutrition Survey (CNNS) and recent updates up to 2026, nearly 27.4% of Indian adolescents are stunted (too short for their age) and 24.4% suffer from thinness, while urban areas face a rising threat of metabolic obesity and anaemia (8). Within adults, about 19·7 % of men and 22·9 % of women were underweight, and 19·6 % of men and 20·6 % of women were overweight (9).

Malnutrition, in all its forms, is responsible for more ill health than any other issue, and the treatment costs are borne by individuals, families as well as public sector health and insurance systems (10). Expensive treatment costs can push poor families further into poverty. Suboptimal physical growth causes life-long susceptibility to illnesses, which leads to lower labour productivity and absenteeism from work, and results in lower lifetime earnings. Poor nutrition during early childhood and adolescence impairs cognitive development, hinders school attendance and reduces attainment, resulting in lost employment opportunities (11). Malnutrition and undernutrition cost India an estimated $10 billion to $46 billion annually, equating to a loss of between 0.8% and 4.2% of its GDP. This economic drain primarily stems from lost adult labour productivity, increased healthcare expenditures, and premature mortality. Beyond physical undernutrition, micronutrient deficiencies alone cost the country over US$12 billion in equivalent economic output every year (12,13,14).

India's nutrition crisis stems from a systemic over-reliance on refined carbohydrates, which constitute over 60% of daily calories. Compounding this, widespread pesticide residues in fresh produce and poor dietary diversity restrict vital micronutrients, triggering a double burden of malnutrition and diet-related metabolic diseases. This macronutrient imbalance directly drives India's status as the global "diabetes capital" and exacerbates the coexistence of stunting and obesity across urban and rural demographics (15,16). The principal causes of the nutrient decline are the degradation of the soil in which crops are grown; developing new high-yield varieties; agronomic factors associated with the commercialization of agriculture; the use of synthetic fertilizers, pesticides, and herbicides to boost food production; improvements in irrigation and the advent of affordable technologies; the introduction of genetically modified food; enhanced air and water pollution; global warming; thinning of the ozone layer; and elevated CO_2 concentration (17,18). In rural India, where agriculture sustains millions, a surprising paradox exists—protein deficiency remains widespread. While rural households may produce or possess protein-rich crops, their daily caloric intake is dominated by staple grains like rice and wheat. Because these cereals lack certain essential amino acids, even when total protein mass appears sufficient, it is biologically incomplete as the body needs protein every day to repair cells, make new tissue, create vital enzymes and hormones, and support a strong immune system (19,20).

India’s agricultural sector responsible for the food security and nutrition of over a billion people has been hit by interconnected distresses arising from fragmented landholdings, severe climate change vulnerability, depleting soil quality and ground water tables and inefficient supply chains. It is extremely important for the focus to pivot to new food production systems that can supplement food quality to ensure larger access to nutritious food. Aquaponics could help increase food production and fill the nutrition gap that is beginning to have an impact on public health as discussed. It is a highly sustainable system, relying on a closed-loop ecosystem where fish waste fertilizes plants and plants clean the water for the fish. This method uses up to ninety percent less water than soil-based farming and completely eliminates the need for synthetic fertilizers, herbicides, and pesticides. Aquaponics systems are sustainable and environment-friendly, as there are no toxic wastes and run-offs from chemicals. Ultimately, aquaponics systems can help urban food growers maximize food yield both in terms of quantity and nutritious quality (21,22,23).

It emerges as a beacon of hope, showcasing how humanity can adapt, innovate, and thrive while preserving the delicate balance of our natural resources. This is extremely important to countries like India where all natural resources are under considerable stress (24,25). This paper analyses its advantages and the challenges that need to be overcome for its large-scale adoption.

II. WHAT IS AQUAPONICS?

At its core, aquaponics is a symbiotic ecosystem where fish and plants support each other. Fish produce

nutrient-rich waste in the water, beneficial bacteria convert that waste into nutrients plants can use, and the plants, in turn, filter the water for the fish. It's a perfect cycle that mimics nature, but on a scale that fits various users. It is a revolutionary approach that combines aquaculture (raising fish) with hydroponics (growing plants in water). The result is a self-sustaining ecosystem where the fish feed on the plants, and the plants in turn keep the fish tank clean. It's efficient, eco-friendly, and perfect for anyone interested in sustainable gardening. Aquaponics perfectly embodies a circular economy by creating a closed-loop, symbiotic ecosystem. Fish waste provides natural fertilizer for plants, while plant roots filter and purify the water for the fish. This dramatically eliminates waste, saves water, and removes the need for chemical fertilizers. AI can optimize system parameters such as water quality, temperature, and nutrient levels, improve resource efficiency and boost crop yields. This synergy between aquaponics and AI offers a new way to address food security and climate change, creating a low-carbon, highly efficient farming system that meets growing food demands while minimizing environmental impact (26,27,28,29).

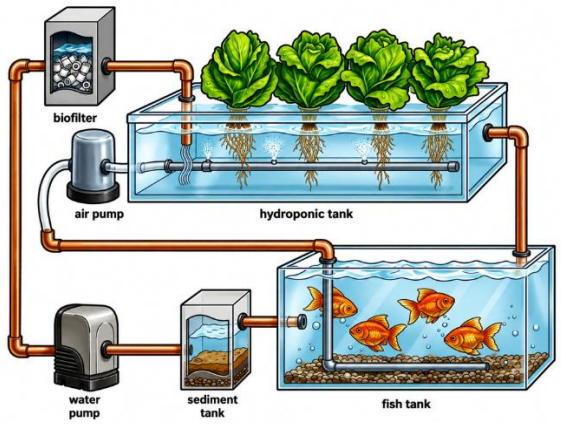


Image source: https://ag.purdue.edu/envision/the-big-idea-hydroponics-aquaponics/

III. ADVANTAGES OF AQUAPONICS

1. Land use Optimization:

Aquaponics optimizes land use by combining aquaculture and hydroponics into a single, closed-loop system. It allows producers to grow both fish and vegetables in the same footprint, utilizes vertical space, and achieves significantly higher crop yields per square foot than traditional soil-based agriculture. It is especially useful for urban farming which often contends with limited or unconventional spaces. Aquaponic systems can be installed vertically or horizontally in warehouses, rooftops, basements, and even shipping containers, maximizing food output per square foot. By repurposing underutilized infrastructure, urban growers can build productive farms without needing expansive land or soil access. Since it co-locates animal protein (fish) and plant production in a single footprint, effectively producing two distinct agricultural yields on the same parcel of land. As aquaponics relies on circulating water rather than heavy, soil-filled fields, it is easily adapted to vertical towers, A-frames, and stacked shelving. Higher Plant Density: Plants can be grown closer together because their root systems have continuous access to dissolved, highly concentrated nutrients without having to compete for space within dirt. Traditional farming operates horizontally, so each plant needs space for roots to spread through the soil, searching for water and nutrients. That is why commercial soil-farming operations require substantial acreage, limiting production capacity where land costs are high (30,31,32,33,34). Vertical hydroponic systems stack growing areas, utilizing three-dimensional space. A single acre of vertical hydroponic greenhouse can produce yields equivalent to 200-350 acres of traditional farmland, depending on the crop. This enables agriculture in urban warehouses, rooftops, and repurposed buildings (35).

India's small farmers stand at a crucial crossroads. Over the decades, their plots have shrunk from an average of 2.3 hectares in 1970 to just 1.08 today and nearly 40% of land is leased informally. This is crucial for India where reports indicate that India now counts among countries with highest yield loss due to human-induced land degradation. Around 3.6 million hectares of croplands were abandoned annually, driven by degradation. This is extremely serious because India supports 18% of the world's human population and 15% of the world's livestock population but has only 2.4% of the world's land area. Unsustainable farming practices, including the overuse of chemical fertilizers and pesticides which depletes soil organic carbon, poor irrigation which causes severe waterlogging and salinization, deforestation intensive tillage and monocropping, overgrazing, climate change and rapid land use change on account of uncontrolled urbanisation are some of the principal factors for this

degradation. The resultant effects include slower growth in food-grain output, displacement of marginal farmers and landless labourers, degradation of groundwater recharge zones, and heightened food-security risks.

Shrinking land holdings are another major crisis in the making. India's small farmers stand at a crucial crossroads. Over the decades, their plots have shrunk from an average of 2.3 hectares in 1970 to just 1.08 today and nearly 40% of land is leased informally.

The rapid urbanization of former rural areas has also led to significant changes in land use, with large swathes of agricultural land being converted into urban developments. Between 2001 and 2010, India lost approximately 700,000 hectares of farmland to urban growth. This trend is especially pronounced in smaller towns and peripheral regions, where land is more readily available for development. While this urban expansion supports economic growth, it comes at the expense of long-term food security. The shrinking availability of farmland threatens India's capacity to sustain agricultural production, especially in the context of climate change, which is already putting pressure on farming systems (36,37,38,39). This where adoption of aquaponics can be of great help.

2. Water efficiency and conservation:

Aquaponics conserves water by using a closed-loop recirculating system where water is continuously recycled between fish tanks and plant grow beds. It consumes up to 90-95% less water than traditional soil-based farming because water is never dumped, and the only losses are from minor evaporation or plant transpiration (40).

In aquaponics, water serves a dual purpose: hosting fish and growing crops, generating two products at once. This isn't the only benefit; the waste from the fish fertilizes the water used to irrigate the plants, and the plants clean the water for the fish. It is a win-win situation. Fish produce ammonia-rich waste, which in traditional aquaculture requires frequent water changes to prevent toxicity. In a standalone fish farming system, the waste can accumulate and become harmful to the fish. However, this system uses biofiltration in which naturally occurring bacteria convert the toxic fish waste into safe, usable nitrates for the plants. Beneficial bacteria, particularly Nitrosomonas and Nitrobacter, play a crucial role in the system. These bacteria convert the ammonia produced by fish waste into nitrites and then into nitrates, which are forms of nitrogen that are essential nutrients for plants. The nutrient-rich water from the fish tank is circulated through the specially designed plant beds made of gravel and expanded clay pellets, where the crops absorb the nutrients from it and the remainder gets filtered through these beds which work as a natural water filter. The plant roots also serve as a natural filter, removing particulate matter from the water as it passes through the growing medium. Additionally, as water flows through the plant beds, it becomes oxygenated through the process of plant respiration. Oxygenated water is then returned to the fish tank, providing the fish with a healthy and oxygen-rich environment, ensuring that the fish have an adequate supply of oxygen for their respiration which is essential for fish survival. This clean filtered water is recirculated back into the fish tank, eliminating the need to dump or drain it. The integration of aquaculture and hydroponics in aquaponics creates a mutually beneficial relationship like nutrient cycling, plant filtration, water recirculation, which will reduce the risk of water pollution and nutrient runoff. This can lead to higher yields of both crops and fish (41,42,43,44,45).

Soil-based agriculture and other fish farming techniques on the other hand, demand tons more water. India supports 18% of the world's population with only 4% of global freshwater resources. Hundreds of millions face extreme water stress due to over-extracted groundwater, severe river and tap water pollution, and depleted reservoirs. Indian agriculture is highly water-stressed, consuming roughly 85-90% of the nation's freshwater resources compared to 69% at the global level. Compared to other leading agricultural producers like Brazil, the USA, and China, India takes 2-3 times the quantity of water to produce the same number of crops. The increasing demand due to the growing population, coupled with declining supply owing to climate change, overexploited groundwater, salinisation, etc., makes it imperative to focus on optimal models of water use in the agriculture sector (46). Growing urbanization, rising industrial demand, and climate change are intensifying competition for scarce water resources. By 2050, an additional 416 million people are expected to live in India's cities, placing enormous pressure on already overstretched municipal water systems. Aquaponics

can help in ensuring food and nutritional security with more efficient and conservative water consumption (47,48).

3. Climate resilience and all year-round produce:

Climate change has added a new dimension to the existing problems by posing a significant threat to Indian agriculture in general and food security in particular. India is also identified as one of the highly vulnerable countries to climate change. Recent studies showed a significant increase in temperature, frequent heat waves, droughts, extreme precipitation events, and intense cyclonic activities. A weakening of the Indian summer monsoon from the latter half of the 20th century has also been reported by, which is the primary water source in India's agricultural sector. Studies have shown that in the short-run (2010–2039), climate change would lower the yields between 4.5 to 9 percent, whereas, in the long-run (2070–2099), it will drastically reduce the yields at least by 25 percent in the absence of adaptation (49,50,51,52). Climate change can also affect the nutritional quality of food crops, with potential reductions in essential nutrients. Moreover, increased food prices and reduced availability can lead to higher rates of malnutrition, particularly among children and other vulnerable groups (53).

The impact of climate change on both terrestrial and aquatic ecosystems is likely to become more progressively pronounced and devastating over the years. There is an urgent need to adapt to climate-resilient food systems that maintain productivity and food availability under changing climatic conditions. Conventional agriculture is vulnerable to erratic weather patterns, prolonged droughts, and soil degradation, which can lead to yield reductions and food shortages. Moreover, it's dependent on seasons. Crops can only be grown during specific times of the year, subject to weather conditions and daylight hours. Aquaponics, however, is not bound by these constraints. It offers protection from these variables through Controlled Environment Agriculture. By operating in controlled environment agriculture (CEA) setups like greenhouses or climate-controlled indoor farms, aquaponic systems support continuous, year-round production. This consistency helps mitigate the effects of extreme weather and seasonal fluctuations, ensuring a steady supply of fresh produce, a key factor for urban food resilience (54,55,56).

By controlling the environment within a greenhouse or indoor setting, aquaponic systems can provide year-round crop production. This consistency in yield not only enhances food security but also opens opportunities for farmers to diversify their produce, cultivate a wider range of plants, and explore unique or exotic species that may not be suitable for the local climate. With the ability to regulate temperatures throughout the year, aquaponics farmers do not have to depend on weather conditions to cultivate organic food (57).

4. Ideal for filling the nutrition gap

According to the latest report by the National Institute of Nutrition (NIN) Indian food is continuously losing its nutritional strength and there's been a significant decline in essential nutrients in fruits, vegetables, grains, and pulses over the last few decades. The potential causes behind the decline in the nutritional quality of foods have been identified worldwide as chaotic mineral nutrient application, the preference for less nutritious cultivars/crops, the use of high-yielding varieties, and agronomic issues associated with a shift from natural farming to chemical farming. Likewise, the rise in atmospheric or synthetically elevated carbon dioxide could contribute to the extensive reductions in the nutritional quality of fruits, vegetables, and food crops. This is the direct fallout of the grave air pollution across the country (58).

India's soil is degrading. Years of imbalanced fertiliser use, declining organic matter and intensive farming have stripped it of essential minerals. Even as the country achieves record foodgrain production, the quality of food is deteriorating as soils lose their nutrients. A report titled 'Healing Soils in India: For Better Crop Health and Human Nutrition', published by the Indian Council for Research on International Economic Relations (ICRIER) found a "clear and troubling decline" in key soil quality indicators over time. The study calls for policy-level interventions to arrest the damage. Soil nutrients are essential for plant growth and yield. But the report shows that Indian soils are increasingly deficient in sulphur, zinc, iron and magnesium, among other nutrients. Data from the 2024-25 SHC cycle indicate that nearly three-fourths of tested soil samples have low levels of soil organic carbon (SOC). This is a key indicator of soil structure, water retention and microbial activity. It is found to be below 0.75 per cent in about 75 per cent of Indian

states. Low SOC levels are associated with reduced crop productivity, higher vulnerability to drought, and increased greenhouse gas emissions (59,60,61).

Reports show lower immune systems, malnutrition and multiple nutrient deficiency disorders due to poor dietary intake and less nutritious foods amongst majority Indians especially among children, adolescents and women. Studies and public health data indicate that a large percentage of Indians ranging from 60% in urban areas to over 70% nationwide fall short of optimal protein intake. Traditional diets are heavily cereal-based and rich in carbohydrates, while awareness of daily protein needs remains low. Protein plays a crucial, multifaceted role in the human body. However, about half of urban Indians remain unaware of protein's vital function. This includes maintaining muscle strength, supporting immunity, and boosting energy levels. Common signs like fatigue, hair fall, or low immunity are often overlooked as indicators of inadequate intake. Physicians caution that a persistent lack of protein can lead to severe health issues. Dr. Vishakha Shivdasani noted that protein deficiency can contribute to muscle loss, metabolic dysfunction, and declining cognitive health. Furthermore, it weakens immunity across all age groups (62,63,64). This could have a huge economic fallout India unless some urgent steps are taken in this direction.

Adaptations like large scale adoption of aquaponics could prove to be very useful. Aquaponics offers a natural and chemical-free alternative. The fish waste provides a rich source of nutrients for plants, and the microbial ecosystem within the system helps to break down these nutrients into forms readily absorbed by the plants. This process ensures that the produce is organic and free from harmful chemical residues, making it a healthier choice for consumers. Nutritionally, food grown in an aquaponic garden is healthier, fresher and genuinely organic (65,66).

Aquaponics also offers a dual benefit by producing both vegetables and fish simultaneously. In the fish tanks, various species, such as tilapia, trout, or catfish, can be cultivated. These fish provide a source of high-quality, protein-rich food. Simultaneously, the plant beds yield vegetables, herbs, and fruits. This synergy is a significant advantage of aquaponics, as it diversifies the food supply and offers farmers multiple revenue streams. Furthermore, fish and plants share the same water, creating a balanced ecosystem (67,68,69).

Moreover, Small-scale aquaponic systems (SAS) are designed to provide affordable, sustainable solutions for individual households or small communities. These systems allow families to produce their own food, including both plants and fish, in a self-sufficient manner, even in limited spaces such as rooftops or urban environments. Small-scale systems are particularly beneficial in urban settings, where access to land and fresh produce may be restricted (70).

5. Limited environmental fall out as compared to traditional farming:

Aquaponics offers massive environmental advantages over traditional soil-based agriculture. It is water efficient and uses 90% Less Water as compared to traditional agriculture. it gives Zero Chemical Fertilizer Runoff. This is a huge advantage as Traditional farming relies on synthetic fertilizers that wash into rivers and cause massive oceanic "dead zones." Nutrients, such as nitrogen and phosphorus, are two of the main macronutrients in fertilizer that promote plant growth. Synthetic fertilizers containing both nitrogen and phosphorus are applied imprecisely to farm fields, often at rates far higher than what the plants need or what the soil can absorb. The excess nutrients from fertilizer leech into surface and groundwater, causing algal blooms and nitrate contamination, impacting drinking water, recreational activities (such as swimming and boating), fishing/shell fishing and marine and aquatic ecology. High quantities of nutrients in water from industrial crop fertilizers and animal waste cause excessive aquatic plant growth a process known as “eutrophication,” which, in turn, causes “hypoxia,” or water that is low in oxygen. Harmful algal blooms (or HABs) occur when aquatic algae grow rapidly out of control. Some types of HABs produce biotoxins, which can kill fish and other aquatic life and cause human illnesses, while others use up the oxygen in the water producing “dead zones,” where aquatic creatures cannot live. Elevated nitrate levels in drinking water can be dangerous to humans. Some pesticides used for agriculture can also find their way into underground water. Aquaponics on the other hand does not use chemicals or pesticides. It relies on the natural synergy between fish and plants. Fish waste serves as a nutrient source for plants, reducing or eliminating the need for synthetic fertilizers and chemical pesticides (71,72,73,74). Aquaponic systems

reduce chemical fertilizer use by 100%. Pesticide use is virtually eliminated, resulting in zero chemical runoff (Sustainable Agriculture Research, 2021). The synergy between the plants, fish and bacteria in the soil and fish waste benefits all components in the system and promotes a circular economy (75,76,77).

Aquaponics effectively cuts down fuel costs and supply chain emissions compared to traditional "farm to fork" agriculture. By allowing highly productive, localized urban farming, aquaponics slashes transportation fuel. Furthermore, it eliminates the need for tractor-heavy fieldwork, synthetic fertilizer transportation, and long-haul food shipping also cutting down on supply chain challenges for the more perishable food items (78,79). Local aquaponic farms can help reduce the distance food travels from farm to table, cutting down on transportation emissions and the risk of spoilage contributing to a more sustainable, local food system (80).it helps cut down the carbon footprint of heavy machinery, transportation, and chemical production used in conventional agriculture which collectively contribute to greenhouse gas emissions. Intensive farming practices deplete soil nutrients and increase erosion leading to increased soil degradation. Aquaponics does not use soil; it doesn't have the same environmental impact as traditional agriculture. this is very crucial for India where years of chemical-intensive agricultural practices following the Green Revolution in the late 1960s have led to extensive soil degradation in India. This has implications for food security, farmers' incomes, and the country's economy (81,82).

Land and soil degradation continue to be a threat to food and nutrition security in India. According to the Food and Agriculture Organisation of the United Nations (FAO) and the United Nations Environmental Programme (UNEP) the imbalanced use of pesticides in agriculture has led to soil pollution to a decline in beneficial insect populations which act as natural enemies of pests. Heavy metal contamination in agricultural soils is already showing adverse effects on human health. Other major concerns are the loss of soil fertility, micronutrient deficiency, low soil organic carbon, residue burning and increased emission of potent greenhouse gases (83,84,85).

As per the latest estimate by the Indian Council of Agricultural Research (ICAR) and National Academy of Agricultural Sciences (NAAS), out of a total geographical area of 328.73 million hectares, 120 million hectares (37 %) are affected by various degrees of land degradation (Department of Agriculture & Cooperation, Ministry of Agriculture, 2015). The most vulnerable to erosion is the topsoil, which causes a depletion in quantity as well as quality of the soil. About one millimetre of topsoil is lost annually in India due to soil (water) erosion at an average rate of 16.4 tons per hectare per year. This comes to over 5.3 billion tons of soil being lost every year due to soil erosion, which results in loss of around 8 million tons of plant available nutrients every year. Soil erosion is a natural process, but anthropogenic interventions and unsustainable land and soil management practices accelerate it (86,87,88).

6. Scalability:

In recent years, urban farming has gained considerable attention due to its accessibility and efficient utilization of limited space, effectively addressing the challenges posed by the rapid urban population growth. Aquaponic systems are highly modular and can be easily scaled up or down to fit almost any space, from a tiny kitchen countertop to a full-sized backyard. The key to downsizing or adjusting your system footprint is properly balancing the biological relationship between the fish tank and the plants. The design and size of aquaponics systems can vary greatly depending on production requirements and specific needs, ranging from small-scale domestic systems to large-scale commercial setups. Commercial systems are typically designed to meet the demand for fresh produce in local shops and supermarkets. On the other hand, domestic systems can allow each home to achieve self-sustainability and produce its own food. Its scalability makes it a versatile system that can be adopted for domestic and commercial needs. Domestic aquaponics systems typically involve cultivating fish and plants in closed-loop systems, typically consisting of a single fish tank, such as an aquarium, and a small hydroponics unit with a maximum area below 50 m^2 (89,90,91,92,93). This is very useful for India where urban spaces are extremely restricted.

IV. CHALLENGES OF LARGE-SCALE ADOPTION OF AQUAPONICS IN INDIA

1. Installation and maintenance cost and complexity:

Aquaponics installation poses significant hurdles, primarily driven by high upfront capital expenditures

(CapEx), technical complexity, and lack of locally sourced materials. Building the infrastructure which includes large fish tanks, plumbing, grow beds, and biofiltration units requires a significant initial financial investment. Setting up systems outdoors makes it vulnerable to extreme weather and temperature fluctuations, which affect both fish and plant health. While, installing durable greenhouses or indoor climate-control equipment increases the initial price tag. Some of the equipment may be difficult to source locally and hence discourages large scale adoption. Relying on specialized vendors or importing parts online can result in higher shipping costs, construction delays, or reliance on improvised trial-and-error replacements (94,95,96).

Studies have shown that the productivity of aquaponics goes up with the use of IoT systems that can monitor and control aquaponics remotely, using sensor-based, actuatorbased, or hybrid systems. Remote monitoring and control, as well as wireless sensors, are crucial elements of IoT in aquaponics. Remote monitoring allows farmers to track water quality, temperature, and nutrient levels, while remote control enables them to adjust settings like water flow rates, lighting, and temperature. Wireless sensors collect data on multiple parameters and can detect issues before they become serious problems. By combining these components, farmers can optimize their aquaponics systems, improving efficiency and productivity. This requires technical expertise which is expensive to hire which makes the system seem complicated for small scale consumers (97,98,99). The complexity of advanced systems may also deter adoption in areas with limited access to technical education or training (100)

Maintenance costs, including sensor replacements and technical support, can be a barrier, making the systems unsuitable for low-cost environments. In countries like India where there are limited capital resources, people may not be ready to risk the investment as the return on investment may not justify the costs, even with efficient monitoring systems (101,102).

2. Energy dependency:

Aquaponics setup requires continuous electricity for aeration, water pumps, and possibly temperature regulation systems (103). A survey of aquaponic practitioners in the USA and internationally shows that about 95% of the respondents relied on power from the main supply grid but because of its unreliability, about 57% of the respondents used alternate sources of renewable energy, e.g., solar cells (Love et al. 2014). Thus, Water pumps and aeration systems must run 24/7. In rural and semi-urban parts of India, grid unreliability and power fluctuations can cause system crashes within hours if oxygen levels drop. This continuous electricity required to run the systems can significantly eat into profit margins and raise the operating costs substantially (104,105).

India has regions of diverse and extreme climates. The intense heat in certain regions can further add up the electricity demand as the systems would require additional energy to chill or heat water to maintain optimal temperatures for fish like Tilapia or Trout, driving energy demands even higher. This adds to which is already high capital investment of the aquaponics setup and thus restricts its adoption and expansion (106).

3. Lack of knowledge and expertise

Aquaponics requires a symbiotic environment with appropriate levels of pH, temperature, oxygen levels, etc. in accordance with the life forms of animals and plants. This requires high-level expertise not just in the field of farming and fish culture but also in the fields of basic sciences and biological systems. This proves to be a significant barrier in India due to lack of knowledge and awareness among various stakeholders, especially farmers and extension workers. Studies conducted even in developed counties such as Canada and UK showed that there is lack of knowledge and expertise and it serves as a significant barrier to implementation of aquaponics (107,108,109)

4. Cumbersome maintenance:

The life forms in the aquaponics unit, i.e., fishes, plants, and microbes, have different optimal pH ranges. There is a constant influx of acid (H^+) from the nitrification of ammonia and of hydroxide (OH^-) or bicarbonate from most plants, both of which keep on trying to shift the pH from the decided value. This makes the maintenance of the system much more cumbersome. There is also the problem of pest and disease management that poses as a barrier for the aquaponic systems. Since the system requires a very delicate balance, there is a need for extra caution in implementing pest interventions (110,111).

5. Social and cultural apprehensions:
India has a large vegetarian population, with a significant number of people viewing the mixing of fish farming with vegetables goes against their dietary preferences. Some may view it is an unnatural method and worry about its long-term health impact. Culturally, there is a deep reverence for soil-based agriculture in India, tied to rural heritage. Soil-less farming and heavy reliance on synthetic or automated water-quality controls can be met with suspicion regarding the "purity" and natural healthiness of the produce. Those who are particular about aesthetics may not like a large structure sitting in their homes (112,113).

V. CONCLUSION

India faces a complex challenge in ensuring food security due to its limited arable land and rapidly growing population. The country holds just 2.4% of the world's arable land yet supports 17.5% of the global population. Each year, India's population increases by 1.19%, adding pressure on its agricultural resources. Agriculture plays a crucial role in the Indian economy and the livelihoods of millions of people in rural areas. The primary source of income for about two-thirds of the population, directly or indirectly, the sector has undergone significant transformations since the Green Revolution in the 1960s, which brought about high-yielding varieties of crops, modern irrigation methods, and fertilizers. However, the country still faces several challenges in agricultural development, including small and fragmented landholdings, low productivity, increasingly shrinking ground water resources, inadequate irrigation facilities, serious soil degradation, and the effects of climate change (114,115).
India ranks among countries with highest yield loss due to human-induced land degradation. Around 3.6 million hectares of croplands were abandoned annually, driven by degradation and nearly 1.7 billion people live in regions where agricultural output is shrinking owing to this. The alarming human toll of land degradation on croplands was highlighted in the State of Food and Agriculture (SOFA) 2025 report released by the Food and Agriculture Organization (FAO) of the United Nations. Shrinking groundwater threatens India's agriculture by inflating irrigation costs and reducing staple crop yields. Because India is the world's largest groundwater user supplying roughly 60% of its irrigation needs from aquifers, this depletion could reduce cropping intensity by up to 20% nationally, and up to 68% in heavily depleted zones (116,117). Aquaponics emerges as a beacon of hope, showcasing how humanity can adapt, innovate, and thrive while preserving the delicate balance of our natural resources (118,119). Within aquaponic systems, a symbiotic cycle unfolds: fish waste serves as vital nutrients for plants, while these same plants act as natural filters, purifying the water destined to circulate back to the fish tanks. This harmonious relationship between aquatic life and vegetation fosters a closed-loop ecosystem, significantly curbing water wastage and elevating the system’s overall sustainability. This method not only produces high-quality organic vegetables and fruits but also sustainable protein sources, addressing the challenges of both food security and water conservation (120).
The Blue Revolution, which transformed India's fisheries and aquaculture sector, has played a crucial role in meeting the growing demand for fish products. However, the conventional methods employed in aquaculture often raise concerns about environmental sustainability, water usage, and the discharge of pollutants. Aquaponics stands out as a pathway to greening the Blue Revolution, offering a holistic and eco-friendly approach to fish and vegetable production. By embracing this innovative system, India can not only enhance food security and rural livelihoods (121,122).
Aquaponics which is the practice of growing plants and fish together in recirculating systems, presents a sustainable alternative that mitigates the environmental pollution associated with conventional fisheries. The integration of aquaponics into traditional aquaculture practices has emerged as a promising solution to address the above-mentioned challenges. The key feature that sets Aquaponic Systems apart is their minimal space requirement, giving rise to the emerging trends of Urban Aquaponics, Urban Agriculture, Urban Farming, Urban Gardening, Terrace Gardening, Vertical Gardening. These systems are advantageous in densely populated areas where space is limited. They can be employed in urban agriculture projects, allowing for efficient use of available space (123,124,125). Aquaponics is critical for India's food and water security, conserving up to 90% of water

compared to traditional farming. Overcoming challenges like high setup costs and energy dependency requires strategic government intervention. Targeted capital subsidies and solar-integrated systems are necessary to drive adoption and prove commercial viability. Government should provide capital subsidies on core equipment (like biofilters and aeration pumps) and solar-powered off-grid setups can dramatically reduce both installation and operational costs.

Special training facilities should be set up to train farmers by offering subsidized training programs and establishing regional model farms to encourage large scale adoption with solar energy back up to create successful template to build larger public support. With government-backed tech grants, systems can use IoT sensors to automate water monitoring, reducing the need for constant, manual technical expertise. Aquaponics presents an opportunity for small-scale farmers who are reeling under low-income stresses, to diversify their income and improve food security. With relatively low space requirements, less water or other input requirements, and the potential for year-round cultivation, aquaponics systems can be adapted to various scales. This is particularly advantageous for small-scale farmers who may not have access to extensive agricultural land. Aquaponics systems can reduce the need for expensive fertilizers and other inputs. Farmers can sell both fish and vegetables, increasing their overall income.

This can open up opportunities for better market prices and increased competitiveness. Training programs and support initiatives can empower local farmers to adopt aquaponics, fostering sustainable practices in rural communities (126,127,128). It also helps solve the problem of malnutrition in the country, a problem which could soon turn into a public health crisis if left unattended. Government should support the growth of niche markets for fresh, locally produced, and sustainably grown products by spreading awareness about its benefits. This could transform the agricultural production and thus, should be pushed forward as a crucial part of agricultural policy.

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