Internet of Things (IoT)-based integrated conceptual framework for sustainable soilless agriculture in developing countries to achieve SDG goals 2, 8, 9, 12, and 13

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Abstract. Objective: *Producing sufficient food is crucial to ensure food security in every country. Efficient farming can be a solution for ensuring sustainability and food security. Bangladesh is the 8th most populous in the world. It has an estimated population of approximately 160 million, with an average of more than 1000 people per square kilometre. Based on recent data, this country requires approximately 70 million metric tons of food by 2025. However, according to the most recent survey in 2021, Bangladesh has less agricultural land. With this amount of land, it would be difficult to ensure that the food demanded is supplied smoothly. To address this problem, alternatives, such as soilless farming, can ease this process. Soilless farming provides the opportunity to grow plants in a controlled environment with fewer resources. This study aimed to develop an Internet of Things (IoT) device framework for soilless farming. By implementing this framework, food production can become a more sustainable, efficient, and alternative solution for food production.* ***Method****: This study proposes an integrated IoT Framework which includes three types of farming, connects them into a single setup, and focuses on ensuring the efficient use of scarce resources, such as land and water. The Internet of Things (IoT) is a modern technology that facilitates efficient and effective soilless farming. This framework includes sensors, automation, and monitoring facilities. This study used qualitative methods and collected data from 50 experts through a semi-structured in-depth survey.* ***Results:*** *Different studies found that using soilless farming productivity increased yield by 20 - 30% compared to traditional farming, which shows the opportunity to choose alternative ways. SDG -2 aims to achieve zero-hunger in developing countries.* ***Originality:*** *By implementing IoT-based soilless farming, yield productivity can be increased compared with traditional farming. This technology could improve food security for over 1.6 million persons ..*

Keywords: *IoT, Soilless Farming, Arduino, Sustainability, Food Security, SDG Goals, Circular Economy, Integrated Farming, CBA, Thematic Analysis.*
JEL Classification: *Q16, Q01, Q55, Q57, O33*

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1. Introduction

The first step in ensuring that a country's economy is stable is food security. Among all physiological needs, food is vital. To guarantee a sufficient food supply, different countries have adopted different approaches based on their ease of use. Countries such as Bangladesh have fertile fields, which are ideal for agriculture. Before the population boom, Bangladesh had enough fields to grow crops that were sufficient for all people. The need for food has also increased among these growing populations. Bangladesh has a land area of 147,570 square kilometres and a population of approximately 175.7 million persons (O'Neill, 2025). Globally, Bangladesh has the eighth largest population and tenth largest population densities. Every year, more than two million individuals are added to the population (Karim et al. 2024). It averages more than 1000 people per square kilometre throughout the country (Khatun et al., 2023). Based on recent data, this country needs approximately 70 million metric tons of food by 2025 (Food and Agricultural Organization of the United Nations, n.d.).

As the population increases, per capita land decreases daily. Agricultural land resources have gradually become scarce. This shortage of land makes it difficult to ensure that the food demand is met. Between the years of 2010-2022 the food dependency rate in Bangladesh was 9.3%–11.2% of the total supply (Markedium Desk, 2023). In the 2022-2023 fiscal year the rate of imported food items was approximately 9.8 million dollars (USD) (FE Online Report, 2023). During the global crisis of covid-19, the world has seen drastic changes occur in the supply chain and economy. After the pandemic, economists suggested that every country should minimise resource dependency on other countries to minimise vulnerability (Economist Impact, 2021).

To address this problem, alternatives, such as closed-loop soilless farming, can ease this process. In soilless farming, there is no need to use soil for cultivation. Instead, substrate-based systems for cultivation are used, which is known as hydroponics. The hydroponic cultivation setup consisted of liquid medium. These are floating systems (floating hydroponics) and the Nutrient Film Technique (NFT). These systems can provide plant nutrients directly to the nutrient solutions (Vought et al., 2024). Some organic (e.g. coconut fibre) and inorganic (e.g. rockwool or perlite) substrates have also been used in these setups. Soil is replaced by organic and inorganic substrates, which reduces the rate of disease due to the production process (D'Amico et al., 2023). Soilless farming provides an opportunity to grow plants in a controlled environment with fewer resources. This ensures the efficient use of scarce resources, such as land and water. The Internet of Things (IoT) is a modern technology that facilitates efficient and effective soilless farming. The growth conditions of plants can be monitored continuously using an IoT framework. Using the IoT Framework, various environmental requirements can be controlled, including nutrient levels, light intensity, temperature, pH, humidity, and sensors which provide real-time information. The data were then examined using machine learning models to predict the optimal conditions and maintain a stable production rate (Devi et al., 2024).

The use of the IoT framework in closed-loop soilless farming provides an opportunity to grow more plants than in traditional farming systems. The most common vegetables are lettuce and chicory, which are produced by soilless farming. Spinach productivity in soilless farming reaches about 2.7 kg /m^2 per year, while traditional farming produces around 16.35 kg /m^2 per year. Soilless farming requires less time for production (Goh et al., 2023).

The analysis of hydroponic systems and traditional soil farming generally yields up to 30% more production per unit area than. A growth rate of approximately 30% and germination rates up to 50% higher can be achieved as soilless farming optimises all nutrient delivery and environmental conditions. The consumption of water can be reduced by 90 %, which is an efficient use of resources. Biomass accumulation can be up to 50% as nutrients are managed and pest interference is minimised (Hydroponic Show, 2024). The IoT enables remote monitoring. Without being physically present in the field, farmers can collect accurate information on soil moisture levels, temperature variations, crop health, and livestock conditions (Kadu et al., 2024). To resolve this problem, hidden-hunger soilless farming has emerged as a sustainable solution. Urban Agriculture practices include the cultivation, processing, and distribution of food in or around urban areas (FAO, IFAD, UNICEF, WFP, and WHO) (Jesuit Social Justice and Ecology Secretariat, 2024).

By 2030, Bangladesh must achieve the 17 SDG goals to become a sustainable country. Some goals align directly with the concept of production through soilless farming. This ensures food security. SDG -2 aims to achieve zero-hunger in developing countries. By implementing IoT-based soilless farming, yield productivity can be increased compared with traditional farming, and can ensure food security for over 1.6 million persons.

The SDG-8 aims at decent work and economic growth. In soilless farming, farmers need knowledge, and by implementing this, the production rate can be increased, leading to economic growth. SDG-9 aims at Industry, Innovation and Infrastructure, SDG-12 aims for Responsible Consumption and Production, SDG-13 aims for Climate Action. These goals align with the concept of soilless farming (Bangladesh Bureau of Statistics & Aspire to Innovate Program, n.d.).

This study's key objective was to propose an integrated framework that aligns with soilless farming, ensures food security, and achieves SDG goals related to food and nutrition. This study proposes a framework for IoT devices in soilless farming that includes hydroponics and aquaponics. By implementing this framework, food production can become a more sustainable, efficient, alternative solution for food production.

This study clarifies the concept of the modern technology used in farming to boost production. Developing countries mostly depend on traditional farming techniques. This can be challenging, sometimes owing to the adverse effects of weather changes. Environmental changes may challenge the production of specific crops and lead to market crises. This has become a normal situation in countries such as Bangladesh. If the amount of production can be maximised, the effects of climate change can be eliminated, leading to market stability. The idea of this study is to combine soilless farming techniques, such as hydroponic, aeroponic, and insect farming, into a framework that will be controlled by the IoT system.

These techniques have much more potential than traditional farming, despite the fact that less than 1% of the research work has been conducted in these research fields in developing countries. Developed countries have improved their farming techniques by identifying alternatives. However, new technologies are not being used in developing countries.

This study raises the following core research question:

RQ 1: How can the use of an integrated IoT framework in soilless farming increase productivity and field yield?

RQ 2: Is these technologies a sustainable option in the economic model of farming controlled by IoT?

RQ 3: Do local farmers benefit from these implementations, and can they adopt the invention rapidly?

2. Literature review

Soilless farming is not a new agricultural concept. It has been practiced for many years. Hanging Babylon gardens is an example of soilless farming. Currently, these technologies can provide solutions to food security (Sambo et al., 2019). Aeroponics is one such innovation; however, its environmental impact is not yet understood. Schmidt et al. **(**2023) assessed the impact of an environmental aeroponic farmhouse container structure in the UK, which also included 19 indicators of the full set. Using the 2021 UK grid, the outcomes demonstrate that the energy requirements drive entire impacts of the estimated climate. Climate change is assessed at 1.52 kg CO2eq per 1 kg of microgreens (pea shoots). The impact of climate change can be reduced through hydroponics.

Karimanzira & Rauschenbach (2019) discussed the improvement of SCADA, ERP, and MES using IoT in aquaponics. IoT-based Predictive Analytics can assist to analyse data more accurately**.** The authors collected data from five demonstration sites in IoT. These data were used to create models of fish, tomato, and their technical components. For the robustness of the plants, the model has filters for remote monitoring, predictive remote maintenance, and economic optimisation. The model generally tolerates temperature variations up to 15%. Econometric models can tolerate a variation in feed ratio size of up to 4% for fish. Lakhiar et al. (2020) presented evidence about currently available soilless systems and explained the modern aeroponic system. This study aims to deliver info regarding the advancement and maintenance tasks essential for practising aeroponic systems.

Garzón et al. (2023) proposed a model which is introduced as a Sustainable Agriculture (TAISA) model with technology adoption and integration, which identifies how production is influenced by technology and ensures quality level through the integrated technology in any ecological cultivation. Sensing is the common technology that is used in aeroponics, which is reviewed in this study.

Engelseth (2023) examined the use of hydroponics in a significant network and created an inter-organizational cooperation through a local and crystal clear form. The proposed conceptual model revealed how this latest technology can be combined to provide an understanding of sustainable production. It raises the question of whether focusing on its impact on logistical processes can help ensure safe and high-quality food.

Hydroponic solutions have opportunities and limitations that have been applied in soilless harvesting systems, and plant mineral nutrition procedure was the key focus. Sambo et al. (2019) showed that direct nutrition absorption is the benefit of hydroponics; the use of pesticides will be less for soilless farming, which is beneficial for crops. Emerging technology facilitates the growth of beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPRs)**.**

Taghizadeh (2021) examined the potential of using domestic hydroponic systems to grow lettuce in urban areas of Sweden. Studies have been conducted to reduce import rates and motivate local food production to become self-sufficient. Sousa et al. (2024) reviewed environmental problems related to global agricultural food systems and food security. They showed that the global population is increasing, and urbanization is growing rapidly, leading to changes in the food system, including production, distribution, storage, and consumption.

Soil moisture level of that can be continuously adapted to achieve maximum plant growing and the effective use of resources. Athani et al. (2017) used different sensors to collect information, which was then processed using a neural network algorithm. Correction factors were used for continuous checking. Soil monitoring has provided a series of observations that indicated the variations in soil conditions over time.

The most significant and elementary parameters for plant growth, that is soil moistness, temperature, and humidity, can be measured using devices such as the microcontroller Arduino Uno, FC28 Hygrometer, and DHT11 sensors. Bhadani & Vashisht (2019) reported that these sensors could identify soil moisture levels, heat, and humidity. These sensors can read and send data to the microcontroller panel for processing.

Oberoi et al. (2017) designed a prototype which allows the sprinkling of fertilisers in macronutrients such as nitrogen and potassium deficient areas. This proves that automated fertilisation units are cost efficient and farmer friendly. It minimises labour requirements for farmers, as the projected component is one-seventh that of the current method.

Other studies focused on the current challenges and future trends in global food production directed by AI. Saha et al. (2024) pointed out the right direction for AI in the agricultural field to meet global food production demands. Systematic Reviews and Meta-Analyses (PRISMA) methodology has Preferred Reporting Items. In this study, agriculture was analysed using artificial intelligence technologies. Oliveira et al. (2023) collected data from 906 relevant studies from five electronic databases and selected 176 studies for bibliometric analysis. The quality appraisal step selected 17 studies for analysis, which showed the benefits, challenges, and trends of the AI technologies used in agriculture.

Haseeb et al. (2020) recommended an IoT-based WSN framework as a structure to smart farming in a comparison of different design levels. To make multi-criteria decision functions, sensors used in agriculture can capture appropriate data and decide a set of group heads. For efficient data transmission, the strong point of the signals on broadcast links was assessed using signal-to-noise ratio (SNR)**.** Security was provided for data transmission.

Sagheer et al. (2021) developed a multi-tier cloud-based Internet of Things (IoT) platform that enhances the greenhouse microclimate. An IoT platform was applied in cucumber cultivation of a soilless technique in a greenhouse which was commercial-sized. The platform was connected through sensors, controllers, and actuators that were placed in a greenhouse to facilitate long-distance communication. The applied platform improved cucumber harvest and enriched its food value. The usage of these platforms also improves water-use productivity and decreases the intake of electrical energy.

In the book by the International Rice Research Institute (1991), the authors have a profit maximisation concept which is valuable. The concept of opportunity cost describes the best use of one resource in an alternative manner. Some sampling methods for classifying economic data are represented in a descriptive manner. Ghosh & Pearson (2025) addressed three key questions in their study: first, whether any of the economic paradigms align strongly with the SDG objectives; second, which strengths and weaknesses must be addressed to achieve various sustainability dimensions; and third, which complementary elements are required to provide better support for sustainable development.

Jain (2024) has composed of navigating the disruptive forces which are reshaping the paradigms of traditional employment. It examines technology-enabled platforms which have facilitated the growth of work and the rise of sectors that have been diversified. It represents technological advancement, consumer behaviour, and a flexible work environment.

Chacua et al. (2024) discussed the factors of supporting the industries and strategic technologies which will impact the economic growth. This study discusses the design of policies related to innovation and addresses recent development challenges. Rudevska et al. (2024) summarised the approaches of modern business that determines the relationship between innovation and financial stability. More than 50 scientific sources were deeply reviewed.

Gulzar et al. (2025) show that using IoT technologies improves the resource efficiency of farmers, which leads to productivity and sustainability. This study, conducted in Jizan, Saudi Arabia, explored the potential economic impact of IoT adoption in the agricultural sector. It also examines the factors that most significantly affect the adoption of IoT technologies among local farmers.

Papadopoulos et al. (2024) provided an overview of the benefits that are delivered by these technologies. The study shows that the use of fertiliser has been reduced by up to 80 % in Recording and Mapping Technologies. In Variable Rate Technologies (VRT), the use of fertilisers decreased by 60%, while the use of pesticides was also reduced by 80%. VRT showed an increase in yield of 62%. Labour and diesel consumption were reduced by 97% and 50 %, respectively. The yield was improved by 10 % to 15 %. The framework facilitates simultaneous reduction in labour and input costs. The integration of digital solutions can enhance agricultural efficiency and sustainability.

Krishna et al. (2024) presented a comprehensive analysis of cost estimation for an automated irrigation system. This method utilises soil moisture sensors and the IoT technology. The designed system can optimise water usage and monitor soil moisture levels.

Medici et al. (2020) have developed a web-tool that supports assessment technology for farmers that have economic benefits in different contexts. Using this tool, it will be easy to access any agricultural stakeholder to evaluate and compare the traditional system and modern technology. Financial viability and environmental impact can be easily measured using these technologies.

Williamson (2007) overviewed the concept of transaction cost economics which is organized around the “Carnegie Triple”. Williamson (2010) has worked on the topic of economics of governance. The topic of governance is the concept of transaction-cost economics. It has the meaning of broad operational content that is integrated into governance and organisational processes (Williamson, 2010).

Avdasheva & Geliskhanov (2025) have reviewed the potential of Transaction Cost Economy (TCE) which is predictive. It focuses on its relevance to reform processes and changes that are profound in the industry and the design of the market. TCE provides the opportunity to understand the economic activity of organisations and markets, as described by Nagle et al. (2020).

The theory of resource-based view (RBV) has explained sustainable advantage in a competitive way through rare and valuable resources. Dhrubo (2025) developed a theory that integrates RBV with Ken Wilber's integral theory. The resource-based view (RBV) is the theory used in strategic management. Beamish & Chakravarty (2021) demonstrated the influence of RBV use on multinational enterprise (MNE) behaviour.

3. Proposed conceptual framework

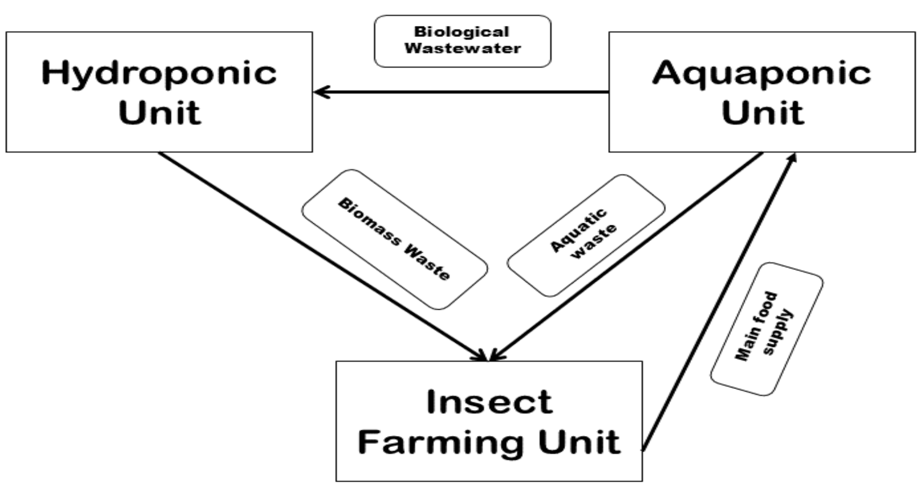
3.1 Proposed IoT framework

In this study, the proposed framework or system architecture was conceived and established to address the difficulties in food supply, material scarcity, and high input demand in developing countries. The proposed system includes three different types of farming setups in a circular cultivation model or can be addressed as closed-loop farming, because the generated waste of the system is used by itself. The system has the ability of automation and control empowered by an accessible and flexible micro-controller named 'Arduino Mega', which is the central unit of the system. The entire system is also operated using green sources like solar energy. As the system includes three different systems interconnected or in a closed-loop farming unit of:

- Hydroponic farming units used to cultivate vegetables and fruit soil free of nutritive water.
- Aquaculture unit, where fish are raised in a healthy and environmentally controlled system.
- Insect farming unit which is a source of protein in the aquatic environment. In addition, it is a source of food and a metrician for different farming units, such as poultry farming.

The system is referred to as a closed loop system because it also uses the circular economic principle. The product of one unit can be added as an input to another unit, and both organic and aquatic dissipates can be the main food resources for insects. Aquaculture wastewater flows into the hydroponic unit which is a beneficial medium for plants, and then goes through an uncomplicated bio-filtration process to the fish tank as clean water. Insects are the main diet of aquaponic systems. For a better understanding, the authors have visualised this in Figure 1, where the interconnection of farming units' dependency on each other is shown.

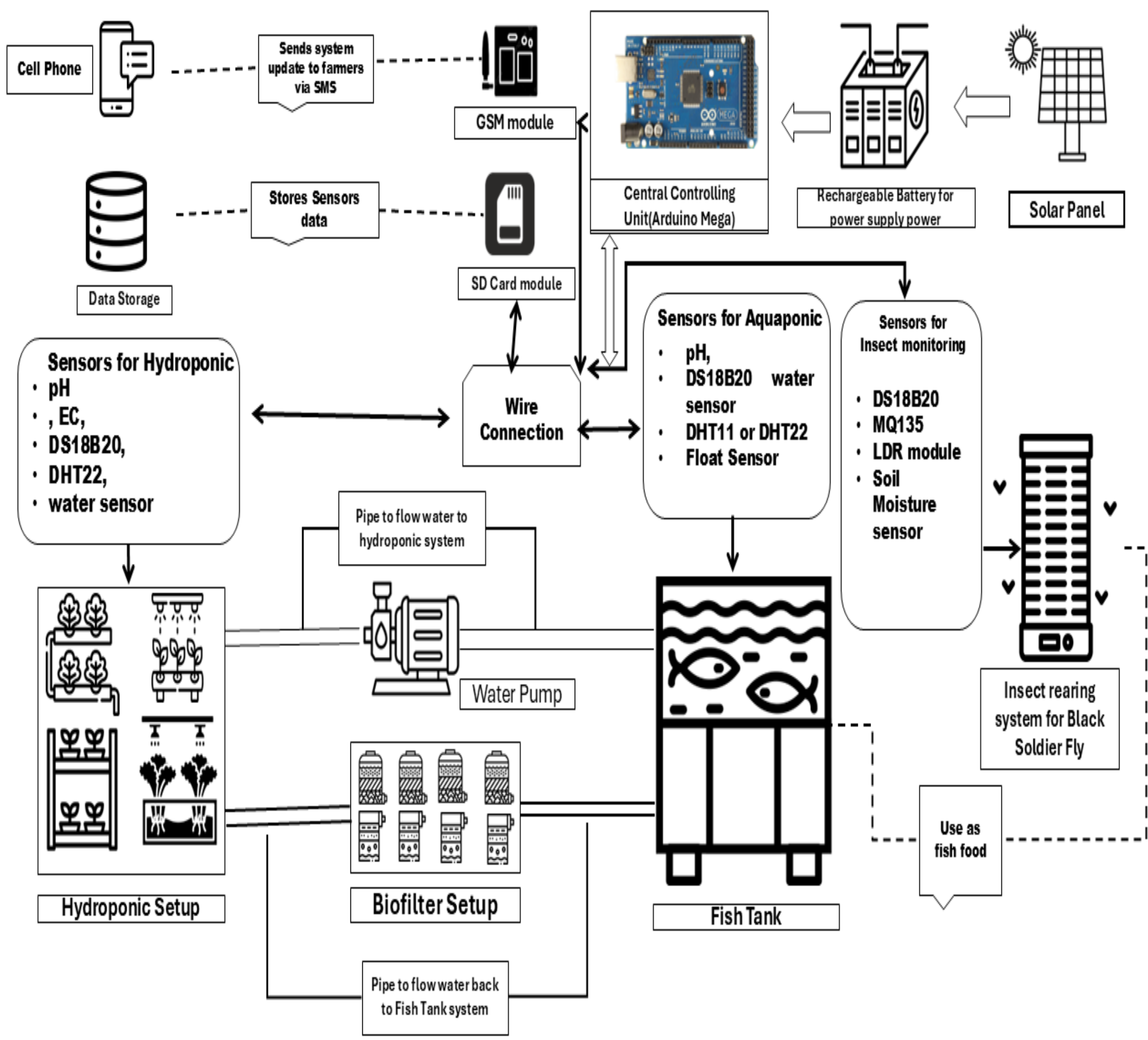
Figure 1. Closed-loop dependency on each other of all farming Units



Source: Developed by the authors.

Different types of sensors operate separately with the Arduino Mega to maintain and control the IoT system. These sensors are used to measure environmental variables such as pH, temperature, humidity, and water level. In this system, many types of sensors (e.g. pH, EC, DHT22, Float, Moisture sensors) are integrated and two main modules, GSM and SD card modules, are used. The GSM module was included in the system because it sends real-time observation alerts via SMS which ensures the availability of the system to its users without any type of internet access. The SD card module stores information on the cultivation structure which can be analysed using any type of computing device. A detailed setup diagram is shown in Figure 2 which is appropriate for deployment in urban cities while sustaining advanced outcomes with minimal operational expenses. Owing to the three enhanced production structure interactions, the proposed framework promotes diversified revenue generation, effective procurement usage, and reduced environmental impact. The proposed IoT framework is appropriate for comprehensive economic expansion. The necessary components can be found in the ecommerce stores and very popular among them are Arduino official store and Alibaba.

Figure 2. IoT Framework for Closed-loop Farming

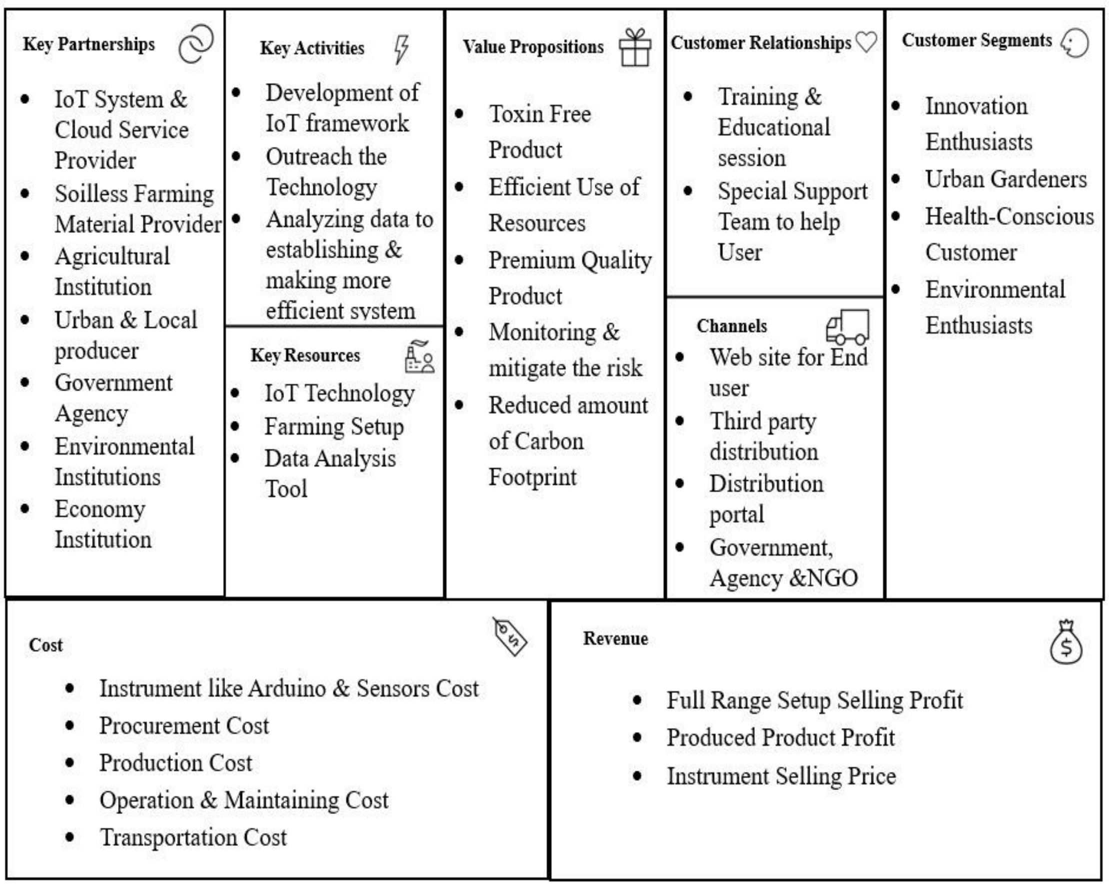


Source: Developed by the authors.

3.2. Business model canvas (BMC) for the proposed IoT farming framework

The term business model commonly indicates the strategy and function of an organisation to execute its business ideas in the market and to identify and speed up the solution process, and Business Model Canvas or BMC can be a very effective tool (Partalidou et al., 2018). To investigate whether the proposed IoT closed-loop architecture is appropriate for commercialisation, a BMC was developed, as shown in Figure 3, which outlines the business strategy by highlighting consumer categories, key sources, value projections, and income mechanisms. This study aims to confirm that the IoT framework is both technically and economically feasible, particularly in the context of developing nations. This model ensures reasonable automation, inexpensive equipment, and an interconnected cultivation setup (vegetables, fruits, fish, and insects) which escalates expediency while maintaining ecological impact.

Figure 3. Business model canvas for integrated IoT farming framework

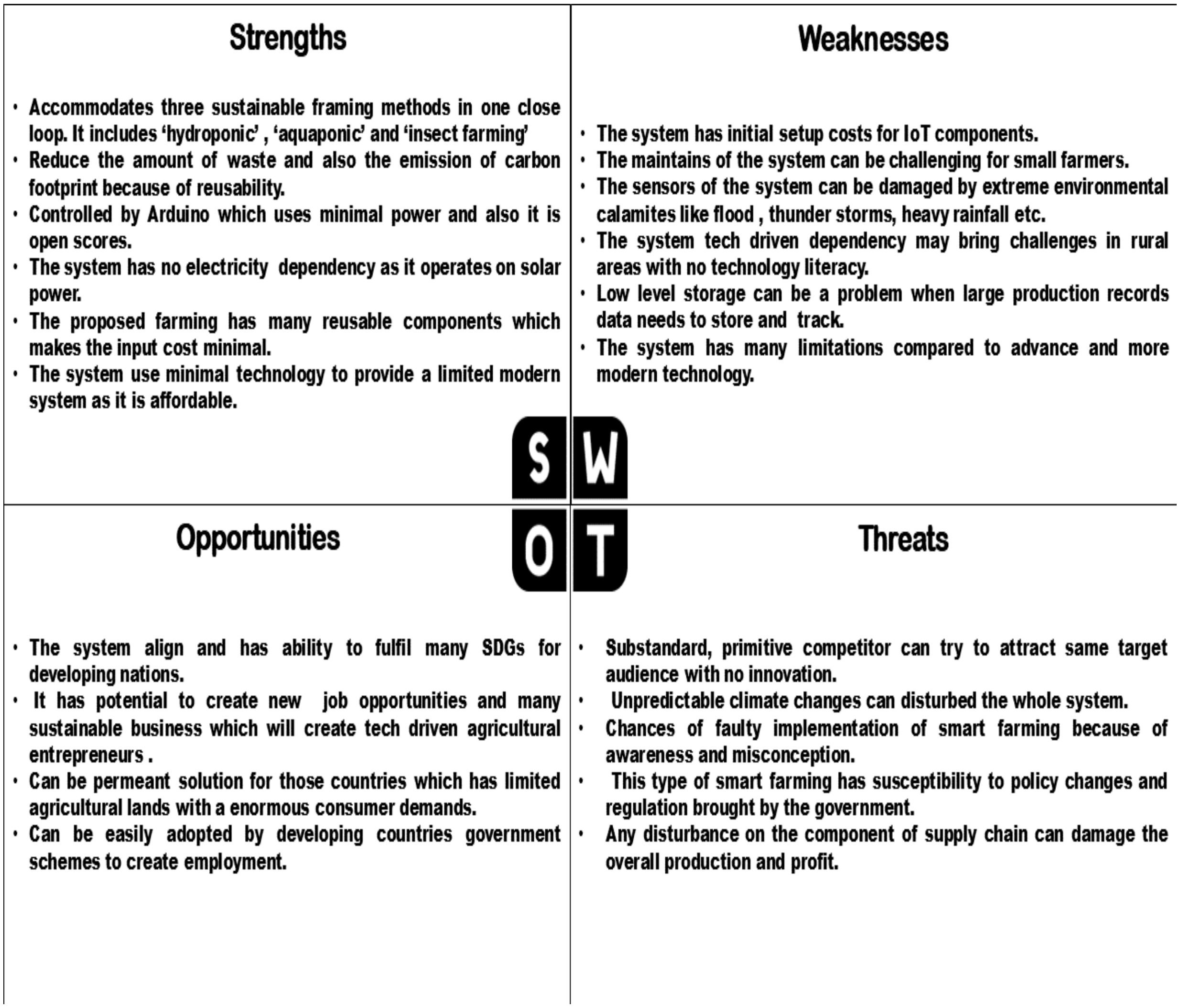


Source: Developed by the authors.

3.3. SWOT Analysis of proposed IoT integrated Farming

A proper SWOT analysis was carried out, as shown in Figure 4, which identifies the pros and cons of this type of agricultural setup. This type of system will be innovative and advanced, but can also be slightly priced for small rural farmers. However, this can ensure minimal carbon and waste emissions. In the future, this category of agriculture will become the first choice for overpopulated countries.

Figure 4. SWOT analysis for IoT setup



Source: Developed by the authors.

3.4. Initial **cost** *evaluation of the IoT framework*

The IoT enabled anytime system is slightly more expensive compared to a traditional cultivation setup, but it becomes feasible in the long run as it brings different categories of features to the working environment that decreases the costs and makes it more economical than other systems, especially traditional ones. The initial pricing of the components for the three setups and other necessary equipment is listed in Table 1.

Pricing of the equipment was taken by Bangladeshi online vendors and originally given in the BDT, and the sensors were mainly the Chinese version. For better understanding and bringing international comparability, the amount is also shown in United States dollars (USD) using the official Bangladeshi Taka (BDT) to USD exchange rate from Bangladesh Bank on 14 August 2025, where 1 USD = 121.4781 BDT (Bangladesh Bank, 2025).

Thus, the total initial cost of the setup amounts to approximately 85,821.25 BDT and 706.78 USD. However, the pricing was based on the information currently available on the website, therefore it can fluctuate and may also depend on the setup size.

Table 1. Initial Capital Expenditure (cost) for the IoT setup

Component name	Usage of equipment	Pricing in BDT	Pricing in USD	Vendors & Sources
Arduino Mega	Central controlling Unit	1790.05 BDT	14.74 USD	TECHSHOPBD.com https://techshopbd.com/ [Accessed on 14 August, 2025]
SD module	Use Storage	250.00 BDT	2.06 USD	RoboticsBD https://store.roboticsbd.com/ [Accessed on 14 August, 2025]
GSM module	Use for sending updates to users	1185.20 BDT	9.76 USD	Robodocbd https://robodocbd.com/ [Accessed on 14 August, 2025]
Temperature Sensor	For monitoring temperature	850.00 BDT	7.00 USD	RoboticsBD https://store.roboticsbd.com/ [Accessed on 14 August, 2025]
Humidity Sensor	For monitoring humidity	626.00 BDT	5.15 USD	RoboticsBD https://store.roboticsbd.com/ [Accessed on 14 August, 2025]
pH sensor	For monitoring pH values	2200.00 BDT	18.11 USD	Electronics.Com.BD https://www.electronics.com.bd/ [Accessed on 14 August, 2025]
Rechargeable battery	To operate The systems	6900.00 BDT	56.80 USD	BDTronics https://www.bdtronics.com/ [Accessed on 14 August, 2025]
Solar panels (626 W)	The main power sources	11500.00 BDT	94.67 USD	BDStall https://www.bdstall.com/ [Accessed on 14 August, 2025]
Water pump	To circulate water	8740.00 BDT	71.95 USD	Walton Plaza https://waltonplaza.com.bd/ [Accessed on 14 August, 2025]
pipes	To carry water to overall system	1000.00 BDT (Depending on the length)	8.23 USD	RFL https://www.rflpipe.com/ [Accessed on 14 August, 2025]
Hydroponic Pots (Considered 250 pieces)	For hydroponic setup	4500.00 BDT	37.04 USD	HydroBangla https://hydrobangla.com/ [Accessed on 14 August, 2025]
Hydroponic chemicals	For Hydroponic Setup	1280.00 BDT	10.54 USD	HydroBangla https://hydrobangla.com/ [Accessed on 14 August, 2025]
Fish Tanks (1500 liter)	For Aquaponic Setup	30000.00 BDT	246.96 USD	RAS Fish Farming https://www.fishpondbd.com/ [Accessed on 14 August, 2025]
Bio-filtration	For water cleaning	10,000.00 BDT	82.32 USD	HydroBangla https://hydrobangla.com/ [Accessed on 14 August, 2025]
Insect box	For insect setup	5000.00 BDT (estimated)	41.16 USD	No e-commerce store Can be buy from Facebook supplier https://www.facebook.com/bsfrcb/ [Accessed on 14 August, 2025]

Source: Authors collected from available online vendors pricing information

4. Economic theories

4.1. Production cost of the integrated system

The IoT integrated system has a high initial cost and must be managed wisely. The calculation of production costs is crucial because a higher production cost of an organisation has a higher impact on the sales and profit of that organisation (Suzan & Nabilah, 2020). Production costs are incorporated into three primary sections: primitive materials, institute manpower, and institute overhead (Sinambela et al., 2022). As presented in Table 1, the price of the system is 85,821.25 BDT, which equals 706.78 USD. For the proposed system, the fixed cost can be estimated using IoT maintenance and equipment changes (e.g. biofilters and lights). Although there is no dysfunctionality in the system, immediate technical support is required. So, the calculation can be done from Equation 2 given below.

Equation 1: Production Cost Formula

$$Production\ Cost = Variable\ Cost + Fixed\ Cost$$

Source: Munro (2024).

4.2. Cost-benefit analysis method for the integrated IoT system

The implementation of IoT-related automation requires a considerably high investment in equipment, incorporating sensors, intelligent devices, and communication devices (Weng et al., 2024). In the proposed conceptual framework, it is necessary to understand and find a way to analyse system costs and outcomes. However, in this study no types of empirical information were used, but for the purpose of methodical analysis, cost-benefit analysis (CBA) was used, in which two commonly used indicators are Net Present Value (NPV) and Benefit-Cost Ratio (BCR). NPV explains the aggregate of the rebated cash discharge correlated with a precise investment (Arnaboldi et al., 2015), and BCR is known as an approach of valuing an investment by differentiating the economic profit of a procedure with the economic expenditure of the exercise (Shively, 2012). The formulas are mentioned underneath,

Equation 2: Net Present Formula

$$NPV = \sum_0^T \frac{B_t - C_t}{(1+i)^t}$$

$$= \frac{B_0 - c_0}{(1+i)^0} + \frac{B_1 - c_1}{(1+i)^1} + \ldots + \frac{B_T - C_T}{(1+i)^T}$$

Source: *University of Arizona, College of Agriculture & Life Sciences* (n.d.).

Here B is the benefit, C is the cost, and t and i are discount rates. The benefit of the system can be calculated from the sales of hydroponic and aquaponic produce, as well as from selling insect larvae to consumers and waste upgrading. The main cost of the system is the infrastructure of the three farming systems, equipment, IoT sensor pricing, and fish food. Finally, the discount rate executes the future costs of the integrated system (e.g. new sensors and fish food) and benefits to its current equivalent values. And also, NPV values plays a crucial role to understand if a project is making profit or not in our case, if the NPV ≥ 0 BDT the project is making profit and if NPV ≤ 0 BDT the project should not be pursue the project (Olivier, 2018).

Equation 3: Benefit Cost Ratio

$$BCR = \left[\sum_0^T \frac{B_T}{(1+i)^T}\right] \div \left[\sum_0^T \frac{C_T}{(1+i)^T}\right]$$

$$= \left[\frac{B_0}{(1+i)^0} + \ldots + \frac{B_T}{(1+i)^T}\right] \div \left[\frac{C_0}{(1+i)^0} + \ldots + \frac{C_T}{(1+i)^T}\right]$$

Source: *University of Arizona, College of Agriculture and Life Sciences* (n.d.).

Here, BCR of the system is calculated using the metrics like benefit and the cos of the system and BCR > 1 will indicate that the proposed IoT system is conveying value creating NPV and also commercially benefit and if the opposite occurs BCR < 1 it is indicating that the system has higher cost than benefit (Hayes, 2025).

4.3. Circular economy method for the integrated IoT system

Limited availability of resources, the transformation of established corporate arrangements, and the shifting towards sustainability in production and consumption can be considered the primary factors behind the Circular Economy (CE), which is an evolutionary change in the industry. Circular Economy has the ability to utilize both sectors of industry manufacturing units and different degrees of value chain (Hatara & Saari, 2025). The elimination of raw commodities and manufacturing garbage, CE, provides and improves the ecological satisfaction and source of inspiration sustainability (Nußholz, 2017). The proposed framework has an in-depth connection with a circular economy. As it is an integrated system, where each system is dependent on each other, one system waste can be beneficial for another system, as shown in Figure 1 in subsection 3.1. The conceptual framework achieves two important objectives: a sustainable way to ensure food safety, and agricultural industry growth. As agriculture has an immediate connection to natural materials, it is assumed to be accountable for the current environmental imbalance (Martínez-Moreno et al., 2024). Circular Economy calculation is usually based upon material volume (Alivojvodic & Kokalj, 2024).

The Circular Economy emphasises escalating the functional material life span by the function of reduction, reprocessing, reclamations, and rehabilitation, which is considered a recognised strategy (Neves & Marques, 2022). The primary focus is to create sustainability in the procurement and resources of the economy for as long as possible (Hartley et al., 2023). In the proposed system it also preserves its raw materials. In aquaponics, water is a very important element and, because of the integrated system, the wastewater goes to the next setup, which is hydroponics, and later returns to the fish tank through a biofiltration process. Thus, the wastewater from aquaponics becomes the nutrient for the plants. After biofiltration, the water is cleaned and returned to the system. This process not only reduces waste, but also ensures minimal environmental impact. Finally, the output from insect farming can serve as the main food source for the fish, while the waste from both hydroponics and aquaponics systems can be used as feed for the insects. The system has the ability to create closed-loop farming where waste is minimal. In 2018, the European Commission (EC) inaugurated a framework to measure advancements in achieving CE (European Commission, 2018). The proposed framework uses an indicator named the Circular Material Usage (CMU) rate to monitor auxiliary ingredients. For CMU calculation the formula is given in Equation 4 given below:

Equation 4: Circular Material Usage

$$\boldsymbol{CMU = \frac{U}{M}}$$

Source: Eurostat (2018).

Here, U represents the total circular material from the system, and M is the total material. The proposed framework has circulating ingredients, such as reused water nutrient waste from three farming setups. Equation 4 can be calculated more clearly using Equation 5, where the parameter M has been replaced with a new variable named Domestic Materials Consumption (DMC) , which is added to the total circular materials of the system (Alivojvodic & Kokalj, 2024).

Equation 5: Calculating Total Material Formula

$$\boldsymbol{M = DMC + U}$$

Source: Eurostat. (2018).

In Equation 5, DMC is defined as the initial input value. For the conceptual framework, DMC can represent the value of a new component which will be added to the system, such as seeds, a new breed of fish, or external nutrients. Circular materials (U) can also be broken down into further variables like Recovery- recycling (RCV_R), Imported Recovery of Waste Bound (IMPW) and finally the Value of Exported Recovery of Waste Bound (EXPW). Accurate calculation can be achieved by subtracting IMPW from RCV_R and then adding EXPW (Alivojvodic & Kokalj, 2024). Incorporating all these variables into Equation 4 yields the final formula, which has is presented as Equation 6 below:

Equation 6: Circular Material Usage (final formula)

$$\boldsymbol{CMU} = \frac{\mathbf{RCV\_R} - \boldsymbol{IMP_W} + \boldsymbol{EXP_W}}{\boldsymbol{DMC} + (\mathbf{RCV\_R} - \boldsymbol{IMP_W} + \boldsymbol{EXP_W})}$$

Source: Eurostat (2018).

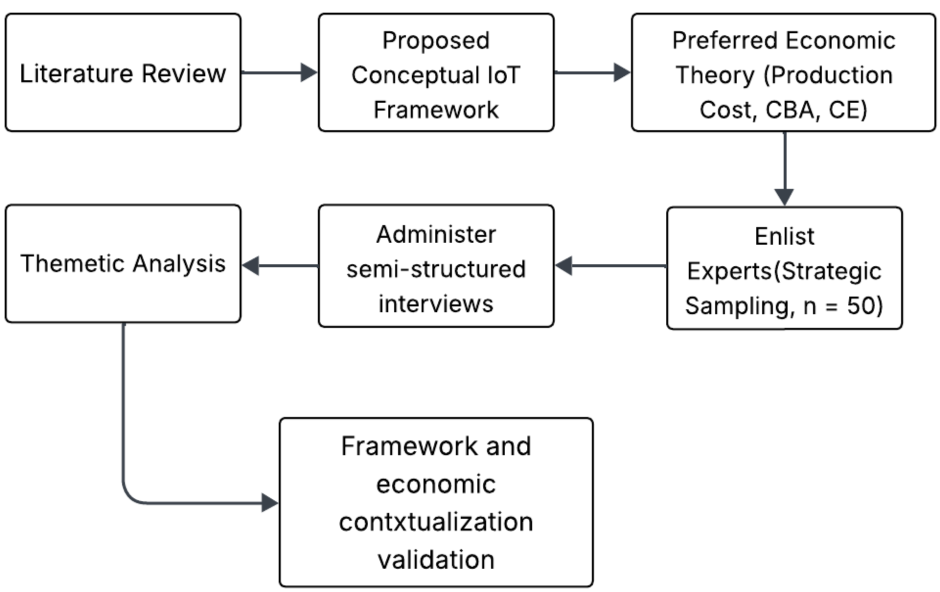
If each variable is defined individually, RCV_R indicates that the plant waste can serve as a food source for aquaponics or insects, while fish waste becomes a nutrient source for hydroponics. Fully unutilised products can be considered undissolved fish food, excess nutrients, or extra equipment added to the system, such as any type of IoT sensors or even lighting which is not properly utilised. Similarly, harvested plants, fish, or insects that leave the system or are sold to external markets are also considered part of this variable.

5. Methodology

5.1. Research design

This study implements a qualitative, research design-oriented approach which explores expert opinions through systematically constructed interviews, which creates a pertinent method of gathering in-depth perceptions of multifaceted phenomena. Qualitative data is commonly distinguished by its focus on expressions instead of numerical values (Ugwu & Eze, 2023). The structured flow of this particular research is presented in Figure 5, where each step helps to fulfil the objectives of the study.

Figure 5. Research Design proceeding flowchart



Source: Developed by authors working procedures.

This study begins with a brief literature review of existing economic and sustainable development theories related to IoT integrated systems and their deployment into the real world. This provides the basis of this research, serving as a less formal method of collecting and synthesizing previous work (Snyder, 2019). In the next step, the conceptual framework of the integrated IoT setup of the three systems in a closed loop was developed to support the idea that an economic theory was adopted by the researchers, which is a cost-benefit analysis (CBA). In the next step, experts and researchers in this specific field were selected, and semi-structured interviews were conducted to go in-depth into the targeted section. However, the main goal of qualitative research is to have a great comprehension of the research phenomena (Polit & Beck, 2010). The information gathered from the interview is qualitative data and is considered as explanatory information which is focused on conceptualization and characteristics, relative to numerical and statistics (Sheldon, 2024). Qualitative exploration requires that the composed data be structured in a meaningful way, and this is referred to as data analysis. Using this analytic interpretation process, the examiner converts large narrative data into intelligible and thoughtful analyses (Liamputtong, 2009). For data analysis, thematic analysis will be considered, as it provides and utilizes a method to convert qualitative data into a purposeful, well-structured, and flexible foundation to recognize, analyses, and interpret the patterns in the dataset and make it understandable (Ahmed et al., 2025). This analysis aims to find and understand the framework, its practical usability, and challenges in real-world environments. Hitherto, this different stage has formed, analysed, and helped reform the thinking process for the study. These stages developed a strong and systematic process for the IoT framework's economic acceptance and implementation difficulties. This process led to the final stage, in which the framework and its technologies undergo economic and conceptual validation, providing a solid foundation for aligning the conceptual IoT framework with a real-world environment. Thus, the approach can be considered well-structured, providing an extensive foundation for evaluating the economic viability and sustainability of the framework using an appropriate methodology.

5.2. Data collection

For any study, data is considered the backbone. To validate the developed conceptual framework, 50 extensive interviews were conducted to gather relevant information. Sustainability was considered when selecting participants with expertise related to IoT. The interview participants included agricultural researchers, educators, small business owners in the agri-business sector.

Participants included farmers with knowledge of sustainable farming. Depending on their availability and preference, the interviews were conducted both in-person (face-to-face) and online (via platforms such as Google Meet and Zoom). Each discussion lasted approximately 45 to 60 minutes, providing sufficient time to analyse their professional expertise and in-depth insights regarding the framework and its validation. Prior to each interview, participants were informed of the study topic in detail. During the interviews, audio recordings were obtained with their consent. In the interview and data collection process, all ethical and moral aspects were directly considered and followed. All steps were taken to ensure the confidentiality of participation. Every audio recording was carefully transcribed to prevent loss of detail due to remembrance or writing. Finally, the transcribed data were systematically coded and analyzed using thematic analysis to identify recurrent themes, emerging insights, and especially those themes deemed significant from the experts' points of view.

5.3. Sample collection

Sampling can be considered a procedure for selecting an appropriate segment of the subject matter of interest. As it is impossible to incorporate an enormous population, a smaller segment of the population is used for data selection of interest. It is easier to compare and reach each individual in the population. Sampling from the population is often considered more practical, enables frequent data collection, and is much cheaper. However, the sample will ultimately be utilised to draw the final decision regarding the segmentation of the population; therefore, it is crucial to select and collect data to analyse and derive by determining how it enters the database (Turner, 2020) The type of the sampling was purposive sampling

The sample consisted of 50 participants, including 16 agricultural researchers, 23 educators, four agro-experts, seven small business entrepreneurs, and farmers who have excellent knowledge of the relevant field. To gather qualitative data, semi-structured interviews were conducted using 15 questions for experts in the targeted field. The selected participants were chosen based on their ability to provide in-depth insights into the field of IoT-integrated systems and their feasibility in the contemporary context.

5.4. Data analysis method (thematic analysis)

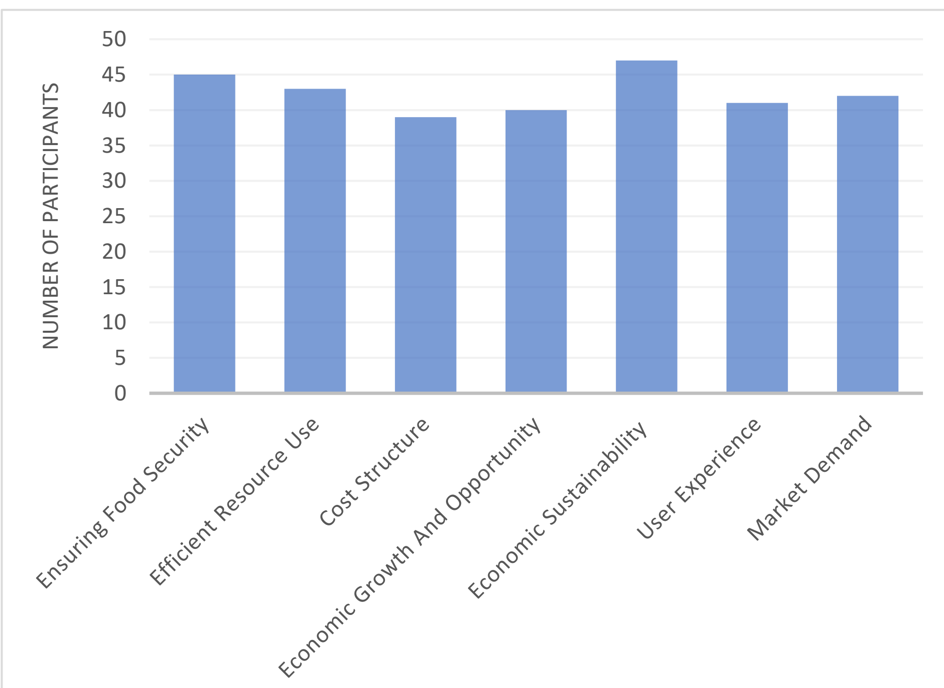
In this study, qualitative data were collected, and Thematic Analysis (TA) was used for the analysis. Thematic analysis is a prominent and utilized technique for evaluating qualitative data types, offering an organized and flexible framework for analysing, classifying, and elucidating patterns from datasets (Ahmed et al., 2025). The data used here have been categorised into different categories according to their boundaries and relationships with the sustainable economy to understand and create a final verdict. The analysis was based on Braun and Clarke's six phases of thematic analysis, as it is one of the most popular methods to find a proper and accurate interpretation result (Braun & Clarke, 2006).

6. Research results and comments

6.1. Thematic analysis

According to Rashid (2023), thematic analysis is a qualitative research method that identifies patterns, themes, and underlying meanings within data. It gives the systematic approach to analyzing textual, visual, or audio data in a structured and comprehensible manner. Thematic analysis organizes and categorizes data into meaningful themes. Figure 6 presents the key issues that have been identified from the expert interviews, which were conducted with 50 industry experts. From their point of view the relation between IoT framework and soilless farming can be explained with seven major themes.

Figure 6. Thematic Analysis - key themes from expert interviews



Source: Based on data that has been collected from interviews (developed by authors).

Theme 1: Ensuring food security

The world population is going to reach 10 billion with a percentage of 34% by the year of 2050. The global pandemic pointed out the fact of self-sufficiency of food. Salisu et al. (2024) has emphasized the fact of exploring various farming techniques to safeguard food availability and affordability particularly in city areas. Traditional farming faces challenges like low-quality soil and extreme fertilizer usage. In urban environments factors like poor soil and fertilizer challenged ecological agriculture and food safety. For producing well food and facing the challenges which arrived post-pandemic have to adopt sustainable soilless technology.

Theme 2: Efficient resources use

Productivity can be increased by using resources critically and analytically. Both technical approaches and economic indicators are important to analyse the factors. Using 90 per cent less water can get a return of 60.6%, offering a potential solution for food security and enhancing climate resilience. Dodiya et al. (2025) show the strong economic viability of hydroponic systems, reporting a payback period of 9.43 months, a benefit-cost ratio of 5.317 and a profitability index of 4.31. Hydroponic systems also offer significant potential when combined with renewable energy sources and automation technologies. However, it faces challenges such as high initial investment, technical complexity and power dependency. With adequate strategic policies and increased awareness, these challenges can be mitigated.

Theme 3: Cost structure

Traditional farming needs land for soil preparation and irrigation systems that are costly. Hydroponic systems need one time expensive set up cost and can be used for many years. In hydroponic systems, plants grow up to 25% faster than soil-grown crops. Faster yield allows for more frequent harvests and quicker returns on investment (Funk, 2025).

Theme 4: Economic growth and opportunity

An economic analysis of this soilless method for sustainable land and water use is provided by the research. In contrast to the traditional farming system, it also addresses socioeconomic aspects. The cost-benefit analysis was used to examine the socioeconomic impact. The findings demonstrate how well the soilless method works for irrigation, increasing agricultural yield and profits. 40% of adopters receive higher incomes than those in the traditional system, which is 20% less. Additionally, the cost-benefit analysis demonstrates that it is highly profitable based on many metrics. The economic and environmental advantages are strong enough to support the claim that soilless agriculture is the most feasible approach for agriculture in light of the expanding sustainability and development trends (Ghanayem et al., 2022).

Theme 5: Economic sustainability

Hydroponic farming is more input-intensive and requires higher initial investment compared to conventional crop production. Therefore, an economic analysis of hydroponics is essential for emerging growers in Bangladesh. This study aims to assess the economic feasibility of hydroponic production systems and compare them with traditional farming methods. The findings revealed that profitability indicators demonstrated stronger economic performance for hydroponics. The feasibility analysis further confirmed that all economic indicators aligned with project acceptability. In particular, the Net Present Values (NPVs) were positive across all polyhouses. Although fixed costs were relatively high, the system generated a high Internal Rate of Return (IRR), consistent with results from previous studies. These findings highlight the potential of hydroponics as a viable agricultural model that can support off-season crop production, meet growing food demand, and mitigate climate change risks in Bangladesh’s agricultural sector (Raihan, 2022).

Theme 6: User experience

Al Mamun et al. (2023) has explained approval of hydroponic technique of agriculture amongst Chinese metropolitans by using both theory of planned behavior and knowledge-attitude-behavior. Attitudes towards hydroponic systems were assessed using partial least squares structural equation modeling. The results highlighted the significant influence of acceptance of diversity, innovativeness, and awareness, on the adoption of hydroponic farming. Also, compatibility was found to have a significant effect on the intent to adopt hydroponic systems.

Theme 7: Market demand

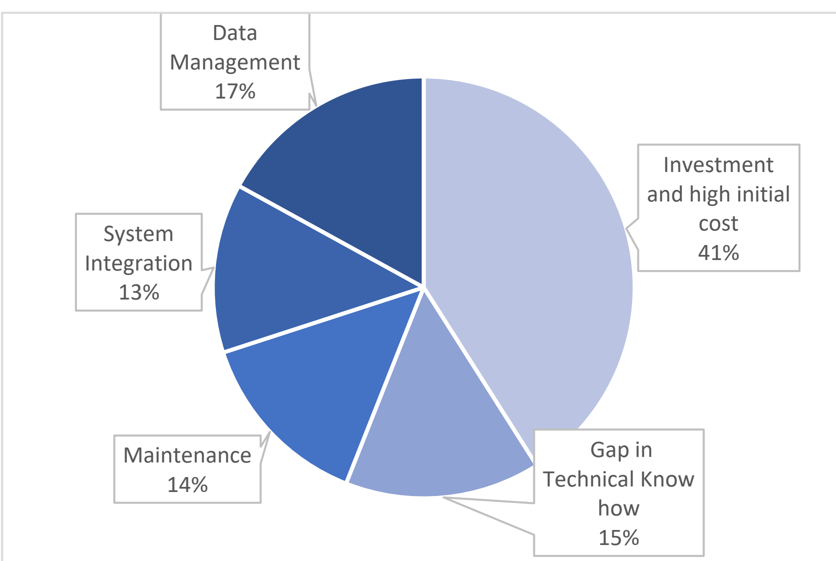
According to a report published by Verified Market Reports (2025), the global market for soilless hydroponic vegetables was USD 9.5 billion in 2024 and is expected to grow further by 2033. The growth will register an annual growth rate (CAGR) of 12.2% starting from 2026.

Table 2. Developing themes and thematic coding

Interview Participate opinion	Initial Code	Final Theme
Eliminate problems related to environmental disasters which cause a fall in productivity and can be a solution to nutritional security	Less Food damage	Ensuring food security
The circular use of water, waste management, and nutrition cycle add value to the competent usage of resources.	Cost of Resources Reduced	Efficient resources use
However, it has a higher initial cost than regular farming, and requires a stronger ROI.	Initial Set up cost is high	Cost structure
This technology has created a new wave of opportunities. Controlled environments for crop production ensure higher productivity than usual.	Higher yield rate with less cost	Economic Growth and Opportunity
Strong linkages in the market also help them gain economic sustainability and policies that support the foundation of the business.	Policies that support strong infrastructure	Economic sustainability
Human errors were significantly reduced as they were monitored at 24/7, and automation was introduced.	Easy to install and track down the pattern	User experience
A specific group of consumers demands these products. Awareness can lead to positive brand perceptions of the technology	Availability of technology	Market demand

Source: Based on the response of the participant, initial code has been presented with brief sentences.

Figure 7. Identified key challenges of soilless farming implementation based on participants



Source: Developed by the authors.

6.2. Conceptual framework validation for integrated IoT system

To validate the proposed integrated conceptual framework, professional assessments, strong literature, and a detailed system design were regulated. As in section 5.3, the experts were chosen based on their expertise and understanding of the agricultural economy, as well as the technology-driven approach. Although their opinions strongly aligned with the developed system design, they agreed with the design and other technological implementations of the framework. However, expert consultation has highlighted three major keynotes which are also the primary motif of the conceptual framework: practicability, value, and difficulties. Experts also strongly believe that hydroponic, aquaponic, and insect farming have potentiality to create sustainability in the food security sector and is also an environmentally friendly approach, but it brings an issue with initial cost; usually, the IoT-driven industry demands a high loyalty to begin with. It can be challenging to deploy a high-yield tech-driven approach toward rural areas where the literacy rate is low and also a major problem of discomfort when adopting new methods to replace traditional beliefs. This type of system cuts down other maintenance costs in the long run, but if a major dysfunctionality is observed in the system, then finding a consultant in rural places can be a challenge. The proposed framework can be one of the best options for the urban and semi-urban places, especially for countries which faces a difficulty of short agricultural land and will be a beneficial factor for the farmers

6.3. Comparison of different farming methods with proposed IoT closed-loop farming

In this section, the analysis of different variables related to traditional farming and soilless-based farming (Hydroponic, Aquaponic, and insect farming) are compared with the proposed IoT setup. The analysis originated from the authors based on theoretical knowledge and the information gathered during the interviews with industrial experts. In Table 3, eight differentiation metrics are presented for the analysis. The metrics were considered based on economic and environmental aspects. From an economic perspective, the consideration was made upon labour wage, investment, ROI time period, revenue, and environment.

Table 3. Comparison of metrics with different farming system vs proposed IoT farming framework

Comparative metric	**Traditional cultivation**	**Hydroponic farming**	**Aquaponic/ aquaculture farming**	**Insect farming**	**Proposed IoT closed-loop System**
Water usage efficacious	Very low	High effectiveness	Moderated level effectiveness	Very low	Very High (As the system reuse it all materials)
Labor expenses	High (a lot of manpower is needed)	Moderated level	Moderated level	Lower than hydroponic and aquaponic system	Very low (as the system is automated)
Recycle of recourses	None of the resources is used again	Partially uses (Nutrient, solution can be reused)	Moderated level (reuse water)	Medium level (waste utilization)	Very High (as it is a close loped setup)
Ecological influence	Very High	Low level	Low level	Low level	Very low
Income stream	Single (Plant/fish/insect)	Single (only plants)	Dual (both fish and plant)	Single (only insect)	Triple (all three in one system)
Initiating funds	Low	Moderately higher than traditional farming	Moderately higher than traditional farming	Low cost	Higher than traditional farming (because of automation enable)

Comparative metric	**Traditional cultivation**	**Hydroponic farming**	**Aquaponic/ aquaculture farming**	**Insect farming**	**Proposed IoT closed-loop System**
ROI time period	Long term	Faster than traditional cultivation	Faster than traditional cultivation	Medium fast	Faster than traditional

Source: The authors developed logical assumptions based on both theoretical and empirical frameworks in agriculture.

6.4. Proposed IoT framing framework alignment with Sustainable Development Goals (SDGs)

Sustainable cultivation has been an important concept in the past few decades, as one of the global challenges is to serve and ensure a food supply for this growing population (Atapattu et al., 2024). For achieving this massive target, the 'Sustainable Development Goals' or 'global goals' were incorporated by all the fellow of United Nations (UN) in 2015 as a worldwide action to eradicate poverty, protect environment and ensure that every individual inhabits in peace and harmony (United Nations Development Programme, n.d.). The United Nations Department of Economic and Social Affairs Division Sustainable Development has 17 goals: providing and creating a better world to live in (United Nations Department of Economic and Social Affairs. n.d.). The proposed framework achieved five of the 17 SDG goals. The proposed framework can ensure sustainability in the fields of food production, economic growth, innovation, and lower environmental impact. In Table 4, the alignment of IoT with SDGs has been described in detail.

Table 4. Proposed IoT-based framing system alignment with UN Sustainable Development Goals (SDGs)

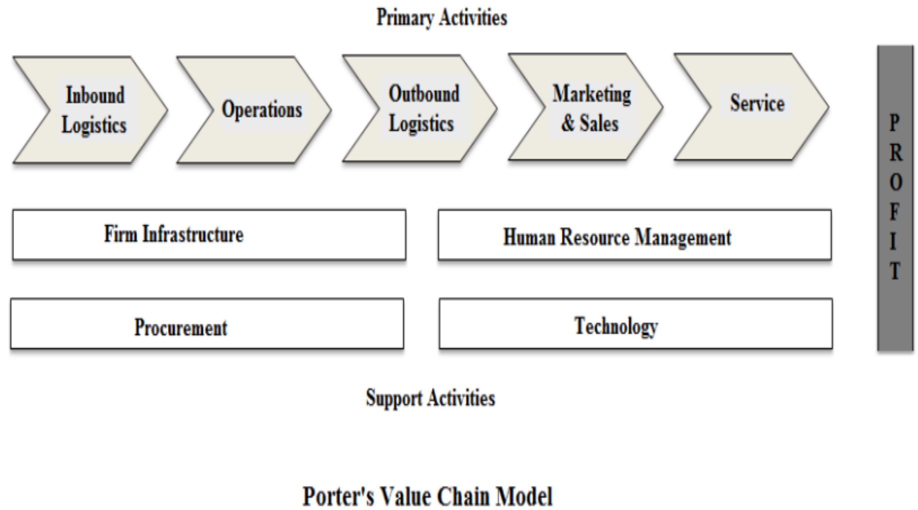
SDG NO.	***SDG Name***	***How the proposed framework can achieve the goals***
SDG 2	Zero Hunger	This system ensures food security by adopting sustainable and environmentally friendly agricultural methods.
SDG 8	Decent work and Economic growth	This can generate a decent amount of employment such as maintenance technicians, marketing, and logistics related to soilless farming and supply chain specialists.
SDG 9	Industry, Innovation and Infrastructure	Integration of IoT in modern agriculture ensure the productivity with a sustainable architecture and a data driven practice
SDG12	Responsible Consumption and Production	This type of framework assures minimal wastage and also the minimal use of the resources like water.
SDG 13	Climate Action	The soilless farming framework monitors and ensures a minimal carbon footprint.

Source: From the report of the United Nations Development Program (United Nations Development Programme [UNDP], n.d.).

6.5. Value chain model

There are several types of theoretical frameworks in supply chain theory. From all the frameworks, Porter's Value Chain provides a better understanding of the supply chain theory used in this study. Michael E. Porter introduced the concept of the value chain. This concept of value chain is straightforwardly detectable in the manufacturing industry, where an enterprise takes raw materials and completes tasks to create a valued product that it sells to consumers. Any company willing to improve efficiency and obtain a competitive advantage must first analyse the value chain. The value chain can be used to identify possible competitive advantages. There are two main components of the Value Chain Strategy: primary activities and support activities (Abbasi, 2017).

Figure 8: Porters value chain Model



Source: (Abbasi, 2017).

Explaining the effective supply chain of hydroponic systems by using Porter's value chain framework.

To build an efficient supply chain, several steps must be followed. The primary objective of the supply chain is to maintain inbound inventory. For production, equipment is common for both hydroponics and aquaponics. Simultaneous sourcing of equipment at the same time will be effective. Basic infrastructure is required for both hydroponics and aquaponics. The production farm will be in a semi-urban area so that transportation for procurement is easy, and the relationship with suppliers will also be strong. The production process will be conducted under one roof, in which different types of vegetables can be grown, and water will be recycled in the flow.

The vegetable production process starts with medium meat preparation, followed by soaking and seed planting, stepping into the growing phase, which includes providing sufficient nutrients and water, and the final step, harvesting, which also includes water emissions from the disposal of exhaust water after recirculation.

The hardware and facilities phases relate to the auxiliary equipment and accompanying infrastructure that enables the soilless farming container farm to function. The hardware stage includes the growth bed container and racking infrastructure, which include pipes, pumps, plastic containers, and other parts, as well as the lighting system and water network. The infrastructure, which has container, growth chamber, HVAC system, and work areas needed for different purposes like germination is included in the facilities. Metal structures and supporting materials are the main elements used at this stage (Schmidt et al., 2023). For the establishment of the firm, nutrition is additionally needed, as farming soil will not be used. These nutrients are needed for the plants to grow; Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Iron (Fe), Boron (B), Copper (Cu), Zinc (Zn), Sulfur (S), Chlorine (Cl), Hydroxyapatite, Amorphous (Sambo et al., 2019).

Nutrients are mixed with water to grow plants. The need for nutrients comes from organic and chemical stores. Half of the nutrients are produced from organic waste, environmental sources, and the rest are supplied from stores.

Agricultural wastes, such as livestock and tail vegetables, can produce nitrogen, phosphorus, and potassium. In addition, proteins, amino acids, fatty acids, and carbon chains are found in the compost process to obtain these nutrients from waste (Xie et al., 2023). Plant nutrients and biogas are sourced from waste management. Biogas is a power source for electrical equipment. Biomass and biomethane are enriched with biogas which can provide a way to integrate industry and people who live in rural areas. The energy sector is now transforming through grid-connected power generation, and people have a tendency to find a renewable way to produce energy. From regulated organic waste, methane can be produced, known as biogas, which is a source of sustainable energy. Biogas is usually produced from biomass substrates basically from vegetable waste. The waste contains cellulose, hemicellulose, carbohydrates, lipids, and indigestible proteins. Using biogas, power and heat can be produced. As per the heating value, falls between 21 and 23.5 MJ/m^3 often, 1 m^3 of biogas is equivalent to approximately 6 kWh of electricity or 0.5 to 0.6 litres of diesel fuel **(**Kabeyi & Olanrewaju, 2022).

In the proposed supply chain, rainwater and ground water are stored in the tank and circulated through a pump which is generated by biogas. As the production house is established in a semi-urban area, transportation costs will be lower than usual. The motive of the designed supply chain is to reduce cost and carbon emissions, which is why dependency on cold storage will be minimised. Before production, if anyone analyses the previous demand pattern and produces the product, inventory in cold storage can be minimised. The maximum product produced is transferred directly to the consumer to serve freshly. By doing this, consumers can enjoy fresh products, and the cost of storage will be less. The proposed supply chain reduces the rate of carbon emissions as the maximum utilisation of resources. The energy required for the setup was produced by the waste management plant. This saves energy and reduces carbon emissions in soilless farming.

7. Case study

Banglaponics: A soilless cultivation technique for tomato in Bangladesh

Owing to drought and decreasing cultivable land, Bangladesh faces major challenges in farming. To address this issue, a new method called Banglaponics was tested for tomato production. This system uses pond water mixed with cow urine and traditional fertilisers. Tomato plants grown in Banglaponics produced a much higher yield (237.85 ± 10.87 g/plant) than soil-grown plants. Growth traits, such as plant height, leaf number, leaf area, root length, and flower number, were also significantly higher in Banglaponics. Chlorophyll content and antioxidant activity were similar between the two methods. However, Banglaponics-grown plants had higher iron (Fe) and zinc (Zn), lower calcium (Ca), and much lower lead (Pb) levels than soil-grown plants, whereas chromium (Cr) and cadmium (Cd) remained nearly the same. Overall, Banglaponics plants appeared healthier and required less water than the soil-grown plants. This method could be a sustainable solution for tomato cultivation in the drought-prone areas of Bangladesh (Khatun et al., 2023).

Bangladesh's IoT hydroponics revolutionizes urban farming

Md. Abdul Awal from Bangladesh Agricultural University has developed an IoT-based hydroponics system to address the challenges of shrinking farmland and rising food demand in Bangladesh. The system uses sensors linked to a microcontroller and a mobile app to monitor key parameters such as pH, temperature, total dissolved solids (TDS), and electrical conductivity (EC) in real time. It automatically regulates nutrient and acid levels, and ensures optimal conditions for crop growth. Field tests with spinach showed high accuracy, with average readings of pH 6.08, temperature 26 °C, TDS 1150 ppm, and EC 1.7 mS/cm, alongside very low error rates (0.001–0.002%). This innovation reduces labour, increases precision, and supports sustainable food production in urban and resource-limited settings. The system holds strong commercial and environmental potential because it improves resource efficiency, lowers energy use, and enables scalable hydroponic farming. Awal's research highlights how IoT integration into agriculture can boost productivity, sustainability, and resilience in the face of climate change and land scarcity (Davis, 2025).

Soilless agriculture for landless poor people: a substitute livelihood through original hydroponic cultivation in flood-prone country like Bangladesh

Table 5. Ongoing soilless farming project on Bangladesh

Project	**Location**
Research on Innovative and Strategic Policy Options (RIPSO) by APEIS	Gopalgonj (Southern Region)
Baira project under CARE Bangladesh, funded by USAAID	Habigang District (Northeast Region)
Wetland Resource Development Society (WRDS) program under the project of Reducing Vulnerability to Climate Change (CARERVCC), funded by Canadian International Development Agency (CIDA).	Chandra (Southwest Region**)**
Adaptation to Climate Change in Bangladesh by Practical Action.	Gaibandha (Northwest Region)

Source: (Saha, 2010).

A unique hydroponic system in Bangladesh recognized Globally

Farmers have developed a floating garden cultivation system. Bangladesh is prone to prolonged flooding. Floating organic beds are composed of water hyacinth, algae, and other plant residues. These gardens were composed of. Farmers can grow various crops and vegetables throughout the year. The technique is environmentally friendly and reduces the hardness of floodwater. This technique provides numerous social, economic, agricultural, and ecological benefits to local populations (Islam, 2023).

8. Discussion

This study was divided into two parts. One part of the study discussed soilless farming integration with IoT devices, and the other part of the study discussed economic theory and analysed the opinions of industry experts. In this study, an integrated IoT device is proposed for the soilless farming sector to be more efficient and ensure food security.

Bangladesh is a developing country, and its economic conditions are insufficient to support advanced agricultural technologies. However, in this study, the proposed setup is feasible for farmers, as it is less costly than the conventional systems. Economic theory highlights the necessity of alternative food-producing sources. To gather expert insights, 50 industry experts were interviewed, and the results were analysed using thematic analysis. These results provide valuable insights into the industry priorities and areas of focus. A real-world case study has shown that soilless farming practices in Bangladesh are currently implemented only on a small scale.

Originality

The use of IoT devices in various sectors is not new, and soilless farming is also a long-standing concept. Based on a literature review, many authors have discussed the principles of soilless farming, and some have demonstrated the IoT device framework and its components. Other researchers have also formulated relevant economic theories and their formulas. The main aim of this study is to propose an integrated IoT framework that aligns with modern agricultural technologies while ensuring food security. The economic analysis shows the feasibility of the proposed framework, which also aligns with the achievement of SDG goals.

9. Practical implementation

This technology can be used in urban areas to produce vegetables on a small scale and provide research institutions with greater opportunities for experimentation. Farmers can use this technology to accelerate crop production and increase efficiency.

9.1. Policy

The government of Bangladesh has a special bank and department for agriculture. These institutes help farmers grow and benefit (Bangladesh Krishi Bank 2024).

9.2. Limitation

The IoT framework in soilless farming has many constraints and limitations. This model is theoretical, and because of the lack of time and resources, it has not been implemented in practice. Economic conditions in rural areas are generally insufficient to support the high cost of sensors, controllers, and monitoring devices. In addition, farmers' technical expertise in operating IoT systems is limited, and effective maintenance may not be possible. Reliable electricity and internet connectivity are essential for system functionality, but infrastructure challenges make consistent operation difficult. Moreover, IoT devices are sensitive to environmental factors such as heat and humidity, requiring careful handling. While there are policies and subsidies for traditional farming, government support for soilless farming remains insufficient.

9.3. Recommendations

- Implement special policies to provide financial and technical support for the setup of IoT-based soilless farming systems;
- Reducing the cost of specialized component through government subsidies or support programs;
- Establish training centers to provide farmer training sessions, to enhance their skilled in using this technology;
- Increase awareness about soilless farming and IoT technologies through common efforts of NGOs and government agencies.

10. Conclusion

In this study, the proposed IoT integrated system introduced an economical and sustainable structure which combines three agricultural setups: hydroponic, aquaponic, and insect farming. The proposed framework emphasizes affordability, sustainability, reusability, and economic viability for the economic progress of a nation. Along with the three-based economic application Business Model Canvas, SWOT analysis and Porter value chain were performed for the proposed structure to make it cost-effective and more feasible. The study also highlighted the production cost analysis and CE for the respective conceptual framework. Economic theory has been used to gain proper knowledge about system cost, durability, and adoption, while Business Model Canvas and SWOT analysis help to analyse the long-term usability, cost, and all types of risk mitigation. With the help of industry experts, the perception of the IoT-enabled setup ensured validation of the structure with current agricultural modifications and acceptance. Moreover, the alignment of the automated system can achieve key SDG goals such as 2, 8, 9, 12 and 13 which can ensure food safety, infrastructure development, economic growth, and sustainable and environmentally friendly food supply.

Authors' contribution: *Introduction, S.K.M.; Literature review, A.T. and R.A.; Methodology and data, A.S. and R.A.; Research results and comments, S.K.M., and A.T.; Conclusion, A.T.*

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