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Off-Grid Smart Hydroponics - PART 1: Market Survey and Concept Generation

Anas Abdul Rahman[1]*, Muhammad Amirul Akmal Mohd Zaidi[1], Ayu Abdul Rahman[2], Nuraffini Mohd Rashidi[1], Khor Jian Yong[1], Nesanraj A/L Selvaraju[1] and Nur Syazwani Nur Shafarizam[1],

[1]Faculty of Mechanical Engineering and Technology, Universiti Malaysia Perlis, Pauh Putra, 02600 Arau, Perlis, Malaysia.
[2]Department of Mathematics and Statistics, School of Quantitative Sciences, Universiti Utara Malaysia, 06010 UUM, Sintok, Kedah, Malaysia.

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ABSTRACT

Rural schools in Malaysia often face limited access to electricity, water, and hands-on STEM learning resources, constraining practical agricultural education. This paper details the design and validation of an off-grid smart hydroponic system developed for a rural Malaysian school through the Service-Learning Malaysia - University for Society (SULAM) programme. Utilising the Nutrient Film Technique (NFT), the system is designed to operate without reliance on grid electricity or piped water by incorporating seven integrated modules which are solar energy supply, environmental sensing, automated pH control, water level monitoring, nutrient dosing, pest deterrence, and IoT-based data feedback. It features dual-microcontroller control, efficient power use and a user-friendly interface accessible to non-technical users. The modular A-frame structure supports 64 plant sites within a compact footprint, optimised for mobility, and educational use. Field deployment at Maahad Tahfiz Sains Darul Muttaqin (MASDAR) achieved a 94% plant survival rate with daily energy consumption below 100 Wh, all without chemical intervention. The system's autonomous function, sustainable energy input, and low maintenance design offer a practical model for smart agriculture and STEM learning in under-resourced settings. The project supports Sustainable Development Goals (SDGs) 2, 4, and 7 by enabling food security, education, and clean energy access through integrated green technology.

Keywords: Hydroponic automation, Educational hydroponics, IoT-based smart farming, Off-grid farming, Solar-powered system.

1. INTRODUCTION

The integration of agriculture, clean energy and automation is increasingly vital in addressing global challenges such as food insecurity, energy scarcity, and environmental degradation. Traditional soil-based agriculture often struggles in off-grid or water-scarce areas due to land constraints, unstable growing seasons, and labour-intensive practices [1]. Meanwhile, modern agricultural technologies remain largely inaccessible to rural communities because of infrastructure limitations, high costs, and a lack of technical literacy [2]. These issues are especially pronounced in rural schools, where limited budgets intersect with the need for sustainable food access and practical STEM education. Tackling this intersection requires a decentralised, low-cost solution that promotes food production, clean energy use, and digital learning without relying on external utilities or complex upkeep.

*Corresponding author: anasrahman@unimap.edu.my

1.1 Overview

Among the various hydroponic methods, such as Deep-Water Culture (DWC), Aeroponic, and many more, the Nutrient Film Technique (NFT) offers a particularly efficient solution for low-resource settings due to its compact layout, low water usage, and continuous nutrient delivery [3]. In this project, NFT was selected as the core method for its suitability to off-grid conditions. NFT systems, as illustrated in Figure 1, circulate a thin film of nutrient-rich water through shallow channels, enabling roots to access both oxygen and nutrients simultaneously, which promotes rapid growth and minimizes risks such as root rot or stagnation [4].

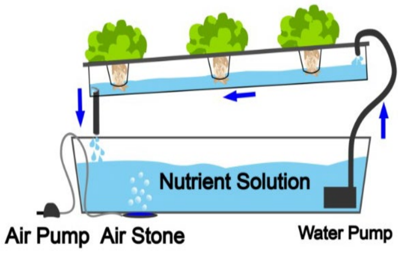
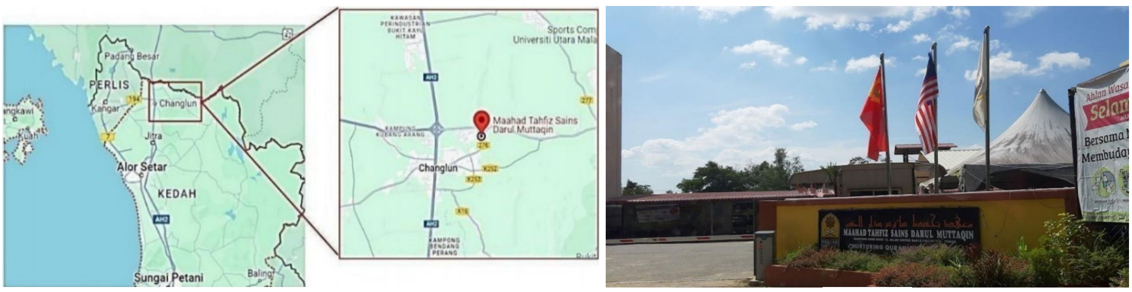


Figure 1: Schematic of NFT system [3].

Despite these advantages, NFT systems are rarely deployed in off-grid or rural schools, where infrastructure is often unreliable. Most commercial hydroponic systems assume stable electricity, a clean water supply, and regular technical maintenance, an assumption that does not hold in many grassroots settings. Additionally, such systems are typically designed for commercial productivity rather than affordability, autonomy or educational accessibility [5]. These gaps limit their relevance in schools that aim to integrate food production with STEM learning in a low-cost, sustainable manner.

This project addresses the gap by integrating hydroponics with solar energy and embedded environmental monitoring to create an autonomous farming solution tailored for underserved settings. By coupling photovoltaic power with IoT-based sensing and control, the system enables real-time nutrient delivery, environmental feedback and minimal user intervention. Designed with educational and rural constraints in mind, such systems simultaneously promote food self-sufficiency and serve as a hands-on learning platform for agriculture, sustainability and automation. These global challenges are exemplified in rural schools such as MASDAR, where infrastructural limitations reflect broader issues of cost, reliance on utilities and sustainability. MASDAR, a rural boarding school in Changloon, Kedah, provides a compelling testbed for this model. Selected under the Service-Learning Malaysia - University for Society (SULAM) initiative, the school combines a willingness to experiment with real infrastructural constraints. While grid electricity and piped water are available, school policy restricts utility use to essential operations, favouring sustainable, low-cost alternatives. Figures 2(a) and 2(b) illustrate the school's location and entrance, highlighting the spatial and infrastructural context of the deployment.



(a) (b)

Figure 2: (a) Location of MASDAR in Changloon, Kedah, (b) MASDAR entrance.

1.2 Problem Statement

Many rural schools in Malaysia, such as MASDAR, face structural and economic barriers that limit the adoption of conventional agriculture and modern educational technologies. Although hydroponics offers a sustainable alternative to soil-based farming, most existing systems rely on stable electricity, piped water, and technically skilled operators, an assumption that does not hold in under-resourced settings. Commercial hydroponic solutions are also cost-prohibitive, complex, and ill-suited for integration into classroom environments.

MASDAR, despite having basic utility access, operates under strict policies that prohibit additional grid or water usage, ruling out most plug-and-play agricultural technologies. Coupled with uneven digital literacy, limited land, and the need for hands-on STEM learning tools, the school requires a compact, off-grid, and user-friendly system that supports food self-sufficiency and technical education without increasing operational burden. This project addresses that need by developing an autonomous, solar-powered hydroponic system designed specifically for low-resource educational environments.

1.3 Background

MASDAR offers strong potential for innovation but faces several limitations that restrict the implementation of conventional agriculture and integrated STEM learning. Although the school has grid and water access, its administration explicitly requested a self-sustaining system with no reliance on utility services. This requires full solar autonomy and off-pipe water management via storage or rain harvesting.

Traditional farming was ruled out due to steep terrain, limited usable land, labour constraints, and seasonal instability [6]. Site assessments also identified low access to farming tools, minimal digital literacy among students, and an absence of real-time environmental monitoring. Pest control remains manual, and automation technologies are unfamiliar to most staff. These realities called for a compact, self-contained hydroponic system that is easy to maintain, off-grid, and able to double as both a food source and an educational tool.

In response, this project introduces a modular, solar-powered hydroponic system designed for MASDAR's technical and educational needs. Developed under the SULAM framework, the system was co-designed with input from teachers, administrators, and students. Priorities included simplicity, reliability, water efficiency, and visual accessibility to support learning in agriculture, sustainability, and smart systems. Table 1 summarises the key site-specific constraints and how they shaped the system architecture.

Table 1: Key Constraints at MASDAR (from Site Assessment).

Category	Challenge	Impact on Project Design
Electricity	No grid usage allowed for the project	Required full energy autonomy via solar power
Water Supply	No piped water usage permitted	Required rainwater collection or stored water with gravity-based distribution
Farming Tools	Limited access to agricultural equipment	Necessitated a self-contained hydroponic unit with low-tech setup
Digital Literacy	Low exposure to automation and smart systems	Required user-friendly interface with minimal technical complexity
Food Supply	Dependence on external food vendors	Motivated integration of a self-sufficient crop production system on-site

These combined constraints highlight the need for a compact, fully off-grid hydroponic system that integrates clean agriculture, smart control, and hands-on STEM learning, while remaining simple, reliable, and accessible for MASDAR's students and staff.

1.4 Objectives

This project aims to develop a fully autonomous, solar-powered hydroponic system tailored to MASDAR's spatial, technical, and educational context. The design aligns with Malaysia's Industry 4.0 (IR 4.0) agenda by combining IoT-based control, digital literacy, and sustainable agriculture in a low-cost, replicable platform [7].

The specific objectives are:

i. To introduce an IoT-integrated solar hydroponic farming system as a platform to indirectly promote STEM learning within the MASDAR school environment.

ii. To design and build a system that integrates sensors capable of detecting water temperature and nutrient solution pH levels, in alignment with Malaysia's Industry 4.0 (IR 4.0) agenda.

iii. To reduce the school's operating expenses by enabling vegetable cultivation through a self-sustaining, solar-powered hydroponic solution.

iv. To implement real-time monitoring of pH within the nutrient solution, allowing responsive control via sensor feedback and automated dosing.

v. To promote sustainability by fabricating an off-grid hydroponic system that runs on solar energy and is adaptable to rainwater-based irrigation.

vi. To develop a portable, modular structure that supports mobility and ease of repositioning, facilitating continuous testing, educational demonstration, and adaptability to varying conditions.

1.5 Scopes

The project scope spans the full lifecycle from system design to field testing of a smart, solar-powered hydroponic platform. The system includes mechanical components such as the structural frame, water tanks, and NFT piping layout, as well as an embedded control system built around microcontrollers and sensors. The system enables real-time monitoring of pH, water level, temperature, humidity, and features a basic user interface designed for educational feedback.

Water usage is managed through a combination of gravity-fed delivery from the rainwater collection tank to the nutrient reservoir and pump-driven circulation through the NFT pipes. With a planting capacity of 64 sites, the system is optimised for growing leafy vegetables such as bok choy and red spinach, which are suitable for classroom use. Designed for ease of observation and minimal technical input, the system prioritises visual accessibility, plug-and-play operation, and relevance to STEM, agriculture, and environmental science learning.

2. NEED ANALYSIS

The success of an engineering solution depends on addressing the needs and constraints of its intended users. To ensure that the proposed off-grid smart hydroponic system aligns with user expectations and local feasibility, a structured market survey was conducted. The survey informed technical specifications, guided design decisions, and validated user priorities for system functionality, sustainability, and affordability. A total of 74 responses were collected, providing insights into hydroponics awareness, feature preferences, perceived benefits, and pricing tolerance within the target community.

2.1 Market Survey Design and Purpose

The market survey assessed public awareness, interest and adoption barriers related to hydroponic farming, with a focus on household and educational use. The questionnaire was structured into three sections, including Section A for demographic data, Section B for general familiarity and attitudes toward hydroponics, and Section C for detailed preferences regarding system features and pricing. Both qualitative and quantitative formats were employed, including multiple-choice, Likert scales, and open-ended questions.

A stratified sampling strategy ensured representation across students, teachers, and household participants. Responses were collected exclusively via Google Forms, with 42 participants from urban areas and 32 from rural areas. Data validation was performed through cross-checking for completeness, consistency, and removal of outliers to enhance reliability.

2.2 Survey Analysis

Survey analysis was conducted across four dimensions, including demographic profiles, general awareness and perceptions, barriers to adoption, and preferred solutions. The inclusion of urban/rural breakdown and stratified sampling enabled a nuanced understanding of adoption barriers and user priorities. These insights were translated into actionable system requirements, directly informing the morphological chart, concept generation, and evaluation process, ensuring that design objectives are systematically addressed through survey-informed decisions.

2.2.1 Demographic Profile

The age distribution of respondents shows that most fell within the 25-30 years (37.8%) and 31-35 years (33.8%) categories, reflecting most young adults who are either early in their careers or pursuing higher education. Younger participants aged 19-24 accounted for 12.2%, while those above 36 represented 16.2%. This profile suggests that the survey captured perspectives from a predominantly youthful demographic likely to be digitally literate and open to adopting new technologies such as smart hydroponic systems.

In terms of gender, female respondents represented 58.1% of the total compared to 41.9% male participants. This slight imbalance may influence the data, as women have often been observed to show stronger interest in sustainability, food security, and educational engagement, potentially shaping attitudes toward hydroponic adoption. The gender distribution, therefore, provides insight into the social perspective that may frame user acceptance of agricultural innovations.

Educational attainment among respondents was notably high, with 89.2% holding a university degree or higher, 6.8% reporting pre-university or diploma qualifications, and only 4.1% having completed secondary school (SPM). While this highly educated profile suggests greater readiness to evaluate and adopt technological solutions, it may not fully reflect the MASDAR student and staff population, many of whom are at secondary school level. Furthermore, 68% of responses originated from urban participants compared to 32% from rural participants, indicating a bias toward urban viewpoints that could overlook challenges faced in resource-constrained rural contexts. These demographic distributions are illustrated in Figure 3(a)-3(c).

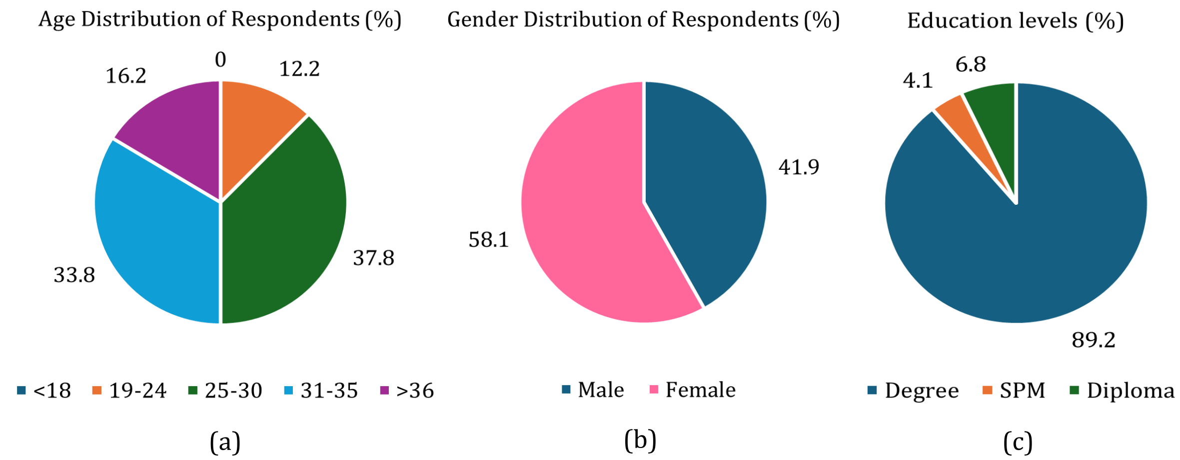


Figure 3: (a) Age distribution of respondents, (b) Gender distribution of respondents, (c) Education level of respondents.

2.2.2 Awareness and Perceptions

Interest in hydroponic farming was notably high, with 79.7% of respondents expressing a desire to learn more. This suggests strong potential for educational and home adoption, especially in urban or resource-constrained contexts where sustainability and space efficiency are priorities. The appeal likely stems from growing awareness of alternative farming methods and their relevance to modern environmental challenges.

Among those disinterested, unfamiliarity with hydroponics was the most cited reason (40%), followed by limited time or space (26.7%), and a smaller group (6.7%) perceived it as too technical. These responses indicate that adoption barriers are more informational than structural. Increased exposure through hands-on workshops, simplified system interfaces, and curriculum integration could significantly improve hydroponic literacy and lower hesitation. The results are summarised in Figure 4(a)-4(b).

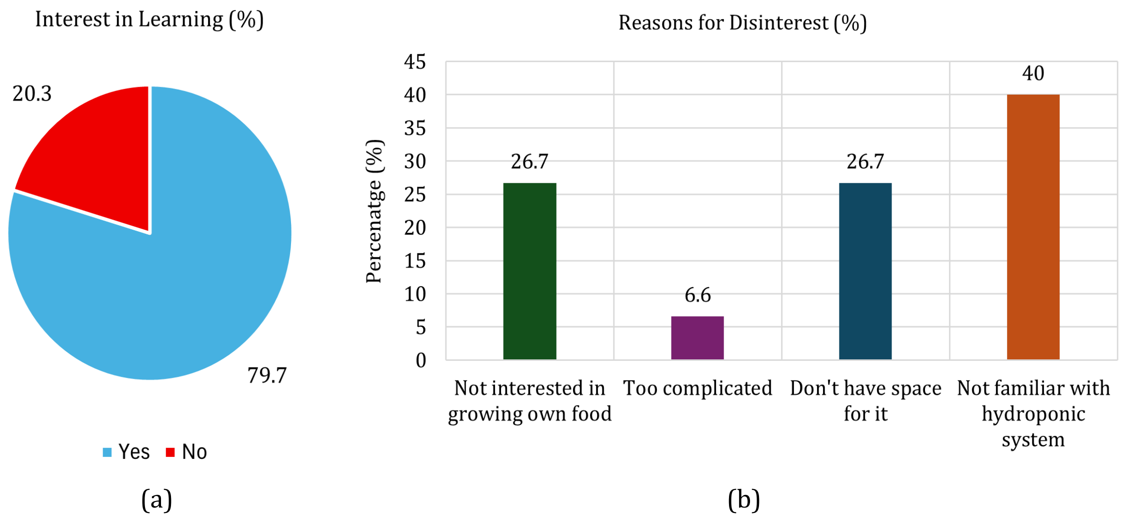


Figure 4: (a) Interest in learning hydroponics, (b) Reasons for disinterest.

2.2.3 Constraints and Perceived Benefits

Respondents identified several challenges that limit traditional home or soil-based farming, with space constraints being the most common. This was followed by a lack of farming knowledge and high maintenance demands, especially among those with limited time or experience. In contrast, hydroponics was seen as a practical alternative. Key advantages cited included space-saving (64.9%), ease of maintenance (51.4%), and water efficiency (44.6%). Additional benefits such as improved yield consistency (41.9%), reduced pesticide use (37.8%), and lower labour needs (35.1%) reflected growing interest in cleaner, more manageable food production methods.

Crop preferences reflected similar practical priorities. Most respondents (93.2%) favoured leafy greens like bok choy and spinach for their fast growth and minimal upkeep. Herbs were also popular (56.8%) due to their compactness and everyday use. Fruiting crops such as tomatoes (16.2%) and cucumbers (12.2%) were less preferred, likely due to longer growth cycles and higher support requirements. These findings suggest a clear preference for low-maintenance crops suited to small-scale hydroponic systems in domestic or educational settings. Results are summarised in Figure 5(a)-5(b).

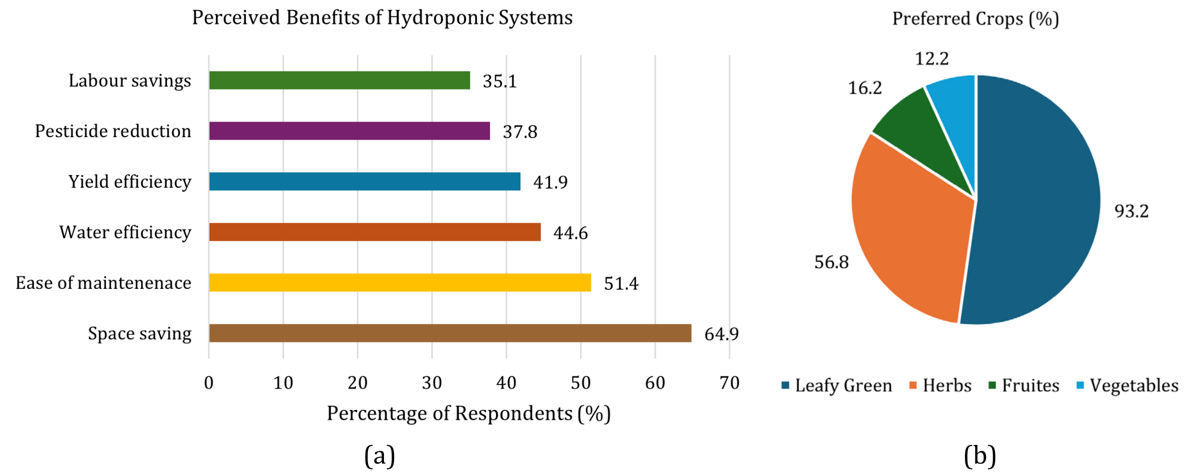


Figure 5: (a) Perceived benefits of hydroponics, (b) Preferred crop types.

2.2.4 Feature Preferences and Pricing Expectations

The final section of the survey examined user expectations for smart hydroponic systems, focusing on purchasing priorities, preferred IoT features, and pricing. Ease of use and low maintenance were most important to 35.1% of respondents, followed by affordability (31.1%), sustainability (13.5%), quality (10.8%), and multi-crop support (9.5%) (see Figure 6a). This indicates strong demand for simple, cost-effective systems that minimise technical barriers, making them practical not only for households but also for classroom adoption.

In terms of IoT features, 39.2% valued automated control, especially for nutrient and pH regulation while 33.8% preferred alert systems for water level or temperature changes. Real-time monitoring (16.2%) and educational value (10.8%) were also noted (see Figure 6b). On pricing, 48.6% expected systems between RM1000-RM2000, and 37.8% preferred RM500-RM1000. Only 8.1% supported options below RM500, and 5.4% were open to prices above RM2000 (Figure 6c). These insights shaped the system's cost ceiling while ensuring core IoT functionality remained practical, sustainable, and supportive of learning objectives in the MASDAR context.

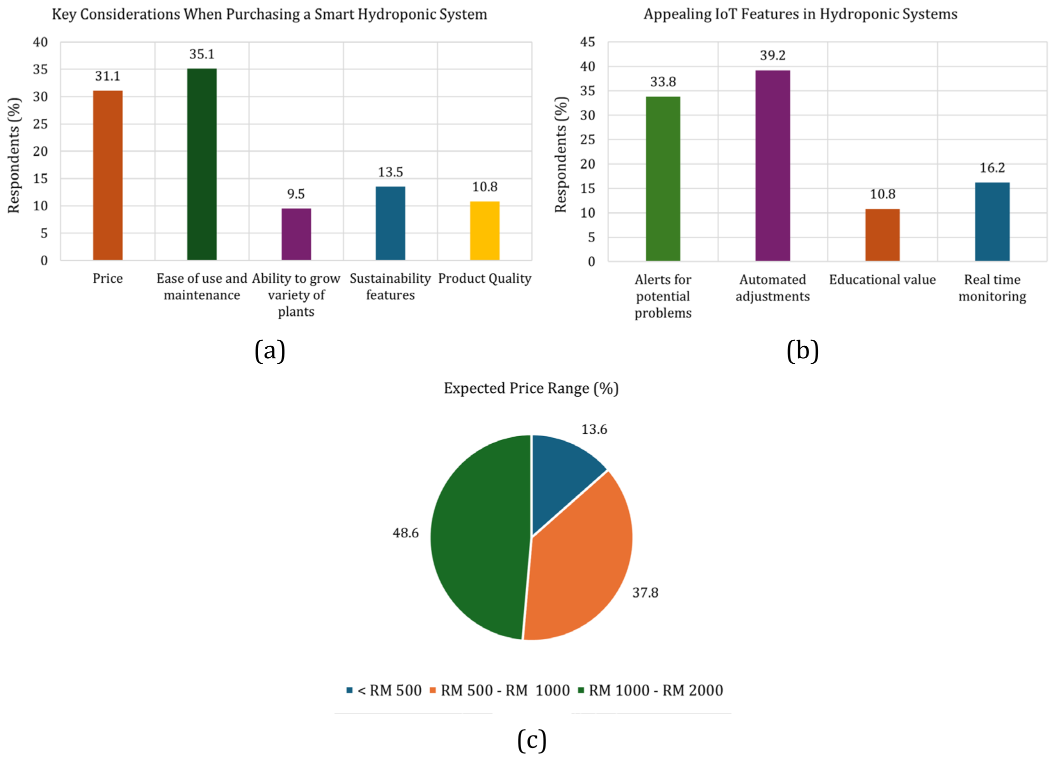


Figure 6: (a) Key Purchase Considerations, (b) Preferred IoT Features, (c) Price Range Preferences.

3. DESIGN SPECIFICATION

The Off-Grid Smart Hydroponic System was developed in response to MASDAR's infrastructural limitations, educational priorities, and the user needs identified through the market survey. Constraints such as the absence of mains electricity and piped water, limited flat terrain, and minimal technical expertise were translated into concrete engineering parameters. This section outlines the design rationale through a Quality Function Deployment (QFD) matrix and finalises the technical scope via a comprehensive Product Design Specification (PDS).

3.1 Engineering Priorities via QFD

A Quality Function Deployment (QFD) approach was adopted to align system development with stakeholder needs. The House of Quality (HOQ) matrix (see Figure 7) integrated inputs from three sources which are, (i) market survey responses detailing user preferences for cost, simplicity, and features, (ii) academic supervision, highlighting educational and technical feasibility, and (iii) feedback from hydroponics practitioners regarding system maintenance and real-world deployment.

User needs such as affordability, ease of use, compactness, and educational relevance were rated on a 1-5 scale and mapped against twelve technical characteristics. These included system size, weight, water storage, sensor performance, and power efficiency.

The weighted analysis identified cost (11.37%), compact system size (10.90%), and low power consumption (10.53%) as top priorities, reinforcing the importance of economic and spatial efficiency in rural deployments. Water storage capacity (9.79%) and maintenance time (8.85%) also ranked highly, reflecting concerns over sustainability and upkeep. Features like mobility and weather resistance, though less critical, were retained to enhance adaptability across different sites.

Number	Important Weight Factor	Engineering Characteristics / Customer Requirements	Water Storage	Power Consumption	Size	Weather Resistance	Maintenance Time	Weight	Mobility	Water Retention Capacity	Filtration Efficiency	Sensor Resolution	Price	Precision and Accuracy of Nutrient Delivery
		Improvement Direction	↑	↑	↓	↑	↓	↓	↑	↑	↑	↑	↓	↑
		Units	litre	watt	m^2	n/a	Hour	Kg	n/a	n/a	n/a	xx.xx	RM	n/a
1	3	Environmentally Friendly	9	9	9	3	1	3	3	9	9	1	9	1
2	1	Weatherproof	9	3	3	9	1	3	3	9	3	9	9	3
3	3	Quality Materials	9	3	3	9	9	9	9	9	9	9	9	9
4	3	Compact Size	3	9	9	3	9	9	9	3	3	3	3	3
5	3	Sustainability Features	9	9	9	3	9	9	3	3	9	9	9	3
6	3	Ease of Use and Maintenance	9	9	9	3	9	9	3	9	3	9	3	9
7	5	Low Price and Maintenance Cost	3	3	9	3	3	3	3	3	3	3	9	3
8	1	Accommodate a Variety of Plants	9	1	9	1	3	3	1	9	9	9	1	9
9	5	Independent Power and Water Supply	9	9	3	1	9	9	1	3	3	3	9	3
10	5	Automated Monitoring and Control System	3	9	9	1	3	3	1	3	3	9	9	3
		Raw Score (2146)	210	226	234	98	190	198	110	162	156	186	244	132
		Relative Weight (%)	9.79	10.53	10.90	4.57	8.85	9.23	5.13	7.55	7.27	8.67	11.37	6.15
		Rank Order	4	3	2	12	6	5	11	8	9	7	1	10

Figure 7: House of Quality matrix mapping user needs to technical specifications.

3.2 Product Design Specification (PDS)

The Product Design Specification consolidates the functional, physical, and operational requirements needed for the Off-Grid Smart Hydroponic System. Developed in alignment with MASDAR's infrastructural constraints and stakeholder priorities, the PDS ensures that system implementation is both technically feasible and contextually grounded. The complete specification is summarised in Table 2.

Table 2: Product Design Specification of the Off-Grid Smart Hydroponic System.

Product Identification

a. **Product Name:** Off-grid Smart Hydroponic System.

b. **Basic Functions:** Method of growing plants without soil, using a water solution instead.

c. **Special Features:**
- Lightweight material and movable
- Crops grow faster
- Require less labor

d. **Key Performance Target:**
- Good filtration system and water system management
- Proper Nutrient Supplied to plants
- Reduce the waste of water

e. **Service Environment:** The system must operate reliably within 20-40 °C and 40-90% relative humidity, reflecting the normal climate conditions in Changlun, Kedah. For design tolerance, the system should withstand 15-40 °C and 20-95% RH, with full outdoor exposure to sunlight and heavy rainfall.

f. **User Training Required:**
- Yes, to ensure that users can operate and maintain the hydroponic system effectively based on their needs.
- A user manual and product specifications are provided to guide users in setup, operation, self-service, and basic troubleshooting.

Table 2: Continued.

Key Project Deadlines

a. **Project Duration**: 2 semesters to complete the project.

Physical Descriptions

a. **External dimensions** (LWH): 2000 mm × 1000 mm × 2000 mm
b. **Internal dimensions** (LWH): 800 mm × 800 mm × 800 mm
c. **Acceptable weight range**: 50 kg
d. **Material:**
- **Structure & Plumbing**: Unplasticized Polyvinyl Chloride (UPVC) pipes, PVC pipes fittings
- **Frame**: Aluminum metal (C-channel)
- **Water Container**: Plastic (food grade)
- **Power Source**: Solar panel
- **pH Sensor**: Differential pH sensor
- **Solenoid Valve Components**: PVC, Brass, Nickel-plated brass, Stainless steel

e. Sensor Specifications (Working Conditions):
- **pH sensor :** Range 0-14, accuracy ±0.1 pH [13], sampling rate once per minute, requires calibration every 2 months
- **Temperature/Humidity Sensor (DHT22):** Temp accuracy ±0.5 °C (-40 to 80 °C), humidity accuracy ±2% RH (0-100%), sampling rate once per minute.
- **Water Level Sensor (Ultrasonic):** Resolution 1 cm, operating range 0-1 m depth, error margin ±5 mm.

Financial Requirements

a. **Pricing policy over life cycle:** Target manufacturing cost: RM1500
b. **Estimated retail price**: RM2500
c. **Warranty period:** 1 year
d. **Expected financial rate of return on investment:** To be determined (TBD)
e. **Level of capital investment required:** RM1800

Life Cycle Targets

a. **Useful Life**: 2-3 years and beyond.
b. **Maintenance Schedule**: Every 3 months.
c. **End-of-Life Strategy**:
- Recycle materials where applicable.
- Reuse functional parts for second-hand product development.
- Recycle all electronic components responsibly.

Market Identifications

a. Target Market
- Educational Institutions
- Hobbyists & Home Gardeners
- Small to Medium-Scale Farmers
- Retail Stores
- Local Markets

b. **Initial Launch**: UniMAP’s IDP day (25 December 2024)
c. **Expected Market Demand**: 50-100 units per year.
d. **Competing Products:**
- Aeroponic Systems
- Aquaponic Systems
- Drip Irrigation Systems

Table 2: Continued.

Social, Political and Legal Requirements a. **Safety and Environmental Regulations**: Compliance with ISO 14001 (Environmental Management Systems) and ISO 9001 (Quality Management Systems) to ensure safety, environmental sustainability, and product quality [8]. b. **Standards and Regulations for Equipment**: All components adhere to ISO 22155 (Hydroponic systems and equipment) and local regulations for agricultural equipment to ensure performance and safety standards are met [9]. c. **Safety and Product Liability**: Do not replace or modify system components with parts that differ in specifications. If the following issues arise, refer to the manuals and specifications: • If any system module doesn't work properly. • If there is a noticeable change in water level. • If unusual mechanical noise is emitted from the pump. d. **Intellectual Property:** The potential for patents will be explored for innovative features of the Off-Grid Smart Hydroponic System.
Manufacturing Specification a. **Hardware Components:** As stated in Bill of Materials b. **Electronic Components:** As stated in the Bill of Materials c. **Assembly Location**: All components will be assembled at the designated project site or place of interest (Plug and Play).

The design process ensured that technical features addressed real-world challenges faced by MASDAR while remaining replicable for similar rural schools. The QFD and PDS together form a grounded engineering framework to support implementation, testing, and future scale-up.

4. CONCEPT GENERATION AND SYSTEM DESIGN

This section outlines the methodology for developing the Off-Grid Smart Hydroponic System at MASDAR. The design, shaped by real-world constraints, prioritised functionality, sustainability, and user needs. Using stakeholder input, site observations, and design benchmarks, it was refined through systematic decomposition and decision-making, resulting in a modular, smart-agriculture system suited for off-grid schools.

4.1 Design Goals and Constraints

Design objectives were derived from pedagogical needs, site constraints and user expectations identified through the MASDAR survey and QFD analysis. These were consolidated into five constraints, which are energy autonomy, water independence, ease of use, affordability, and spatial resilience, as summarised in Table 3. The constraints defined the design boundaries and simultaneously informed innovations in energy management, structural configuration and user interaction.

The constraint of energy autonomy required the system to operate solely on solar energy, avoiding any dependency on MASDAR's grid electricity. Water independence was addressed through gravity-fed irrigation and rainwater collection, eliminating reliance on piped supply. To enhance educational value, the system required intuitive interfaces and transparent component layouts for non-technical learners. Budget limitations necessitated a total system cost under RM1500, prompting the use of modular low-cost components. Finally, spatial constraints at MASDAR called for a compact, mobile, and weather-resistant structure suitable for both indoor and outdoor classroom use.

Table 3: Design Constraints for the Off-Grid Smart Hydroponic System.

Constraint Category	Design Target	Rationale
Energy autonomy	Operates entirely on solar power	Complies with MASDAR's no-utility policy
Water independence	Uses stored rainwater or a gravity-fed system	Avoids reliance on piped water infrastructure
Educational usability	User-friendly interface and clear feedback	Enables hands-on learning for non-technical users
Affordability and ease of maintenance	Total cost under RM1500 and modular subsystems	Matches survey pricing expectations and allows cost-effective upkeep
Spatial and environmental	Compact, portable, and weather-resistant structure	Suits MASDAR's limited flat terrain and need for outdoor use

4.2 Engineering Input Sources and System Validation

The concept generation process was shaped by a triangulated foundation of engineering inputs, which are (i) site-specific environmental and infrastructural constraints, (ii) survey-driven feature priorities and (iii) validated reference designs from literature and commercial case studies. These inputs guided the formation of a robust system architecture, systematically divided into power management, sensing and control, and mechanical hydroponics infrastructure. Each subsystem was tailored for autonomous, off-grid operation, aligned with MASDAR's utility and educational limitations.

Site analysis revealed restricted land space and a lack of water and electricity connections, prompting the use of solar energy and compact structural profiles. User surveys emphasised simplicity, real-time monitoring, low maintenance and automated control as key preferences. These user priorities necessitated the integration of pH sensors, simplified dosing mechanisms and wireless data visibility. Reference literature, such as the work by Kim et al. [10], demonstrated that smart hydroponic systems can achieve >1300% yield improvements with sub-400 Wh/day energy use using dual-microcontroller designs and passive energy harvesting. While their model utilised a DWC system and wind-solar hybrid power, our adaptation focuses on a lighter NFT structure, lower energy consumption, and simplified automation suited for MASDAR.

The selected configuration uses only solar power, consistent with the study's energy profile. Sensor choices match reliability and accessibility standards. Unlike the DWC approach in the reference system, the MASDAR design leverages NFT for its efficiency with low water volumes and better compatibility with compact layouts. These comparisons, as illustrated in Table 4, confirm that the proposed system meets the technical, operational, and educational requirements for deployment in MASDAR's unique rural context.

Table 4: Summary of Smart Farm System Performance and Relevance to MASDAR Design.

Parameters	Reference System	MASDAR System
Energy Source	Solar + Wind	Solar only
Energy Usage	400 Wh/day	Below 100 Wh/day
Autonomy	Run 2.5-day, 1 day of solar charge	Run off-grid for 1 day
Sensors Used	Temp & Humidity, Water level	Temp & Humidity, pH &Water level, Ultrasonic Transducer,
System Control	Fully automation	Only for the Nutrient delivery system
Hydroponic Method	Deep Water Culture (DWC)	Nutrient Film Technique (NFT)
Crops Grown	Lettuce	Bok choy and red spinach

The decision to prioritise bok choy and red spinach was made due to their fast growth cycles, resilience to fluctuating tropical conditions, and minimal nutrient demands, making them ideal for classroom use. Both crops are visually distinctive, allowing students to easily observe growth stages, while their short harvest periods (30-40 days) align with academic schedules. Furthermore, these leafy vegetables are widely consumed in Malaysia, providing cultural and dietary relevance that strengthens the system's role as an educational tool linking agriculture, health, and sustainability.

4.3 Functional Decomposition

To facilitate system integration and user understanding, the hydroponic system was decomposed into three principal domains, which are power supply, control, sensing, and hydroponic infrastructure. Each domain was assigned specific responsibilities and physical subsystems. This structured decomposition enhanced design clarity, modularity, and testability while also serving as an educational scaffold for students learning embedded systems and smart agriculture.

4.3.1 Physical Decomposition

The physical decomposition of the Off-Grid Smart Hydroponic System, illustrated in Figure 8, categorises the hardware into three primary subsystems, which are power supply, control and sensing, and structural hydroponic infrastructure. This modular breakdown improves system integration, supports targeted troubleshooting, and enhances educational demonstration value.

The power supply subsystem governs energy generation, regulation, and storage. It includes a photovoltaic energy source, a controller to manage charge input, and an energy storage unit, ensuring continuous energy availability for day and night operation and fulfilling MASDAR's off-grid autonomy requirement. The control and sensing subsystem is divided between two microcontroller units. The first manages core hydroponic operations, including pH solution monitoring, irrigation control, and remote data access, while the second handles environmental interaction and protective functions such as ambient monitoring, pest deterrence, and user interface control. This dual-microcontroller architecture supports distributed control, improving redundancy and modularity.

The structural hydroponic subsystem supports the physical cultivation process. It includes the hydroponic support frame, nutrient delivery network, fluid storage units, and mobility features. The design accommodates selected leafy vegetables, such as bok choy and red spinach, chosen for short growth cycles, classroom visibility, and hands-on learning opportunities. Mobility elements facilitate repositioning for sunlight access, maintenance, and instructional activities, while the frame and tanks ensure stability and continuous nutrient film flow.

This decomposition aligns with engineering best practices and reinforces the project's core objectives of autonomy, maintainability, modular learning, and scalability in off-grid educational settings. Beyond operational functionality, the modular layout serves as a tangible teaching tool, helping students understand smart agricultural systems and embedded system design. A complementary visual representation of the functional interactions between these subsystems is provided in Section 4.3.2 (Figure 9), further illustrating the system's modularity and operational flow.

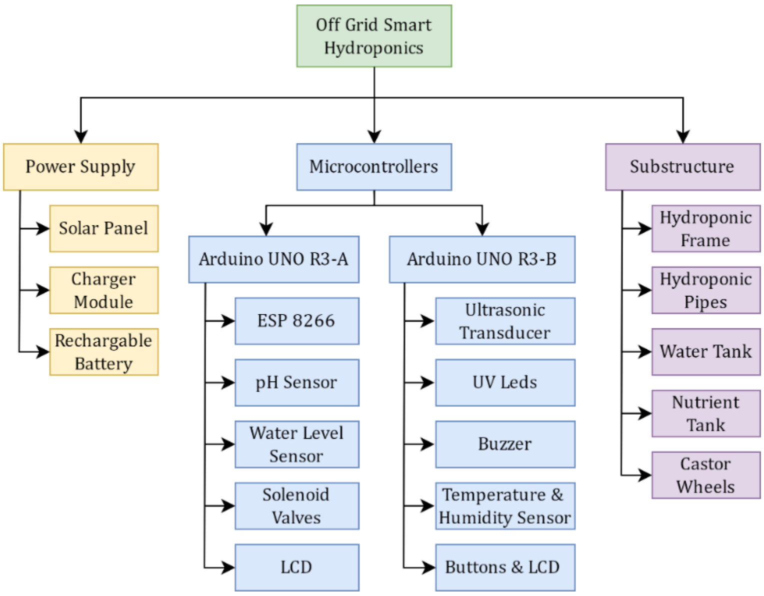


Figure 8: Physical Architecture of the Off-Grid Smart Hydroponic System.

4.3.2 Functional Structure

The Off-Grid Smart Hydroponic System is organised into seven functional modules across three primary domains, which are energy supply, control and sensing, and hydroponic infrastructure (Figure 9). These modules interact via defined energy, signal, and user pathways to support autonomous operation while enabling instructional use within MASDAR's school context. The modular architecture improves reliability, facilitates fault isolation, and reinforces educational value.

The energy supply domain ensures continuous off-grid operation through a solar-powered generation module, regulated charging interface, and onboard energy storage. This configuration provides uninterrupted electrical power to all control and actuation subsystems, even under intermittent solar conditions, satisfying MASDAR's autonomy requirement.

Control and sensing are implemented via a dual-microcontroller framework. Arduino Uno A manages core hydroponic operations such as real-time pH and water level monitoring, nutrient dosing, visual feedback, and cloud communication. Arduino Uno B handles environmental sensing and pest deterrence through ultrasonic activation. Wireless modules enable alerts and remote observation via Telegram Bot, and both microcontrollers operate synchronously to enhance resilience and modularity.

The hydroponic infrastructure domain governs nutrient delivery, water circulation, and structural support. Nutrient dosing is automated based on sensor feedback, while circulation is maintained through pumping and gravity-assisted flow paths to sustain a continuous nutrient film over roots. The portable frame supports structural stability, ergonomics, and ease of repositioning for sunlight access, maintenance, and instructional activities, accommodating classroom crops such as bok choy and red spinach.

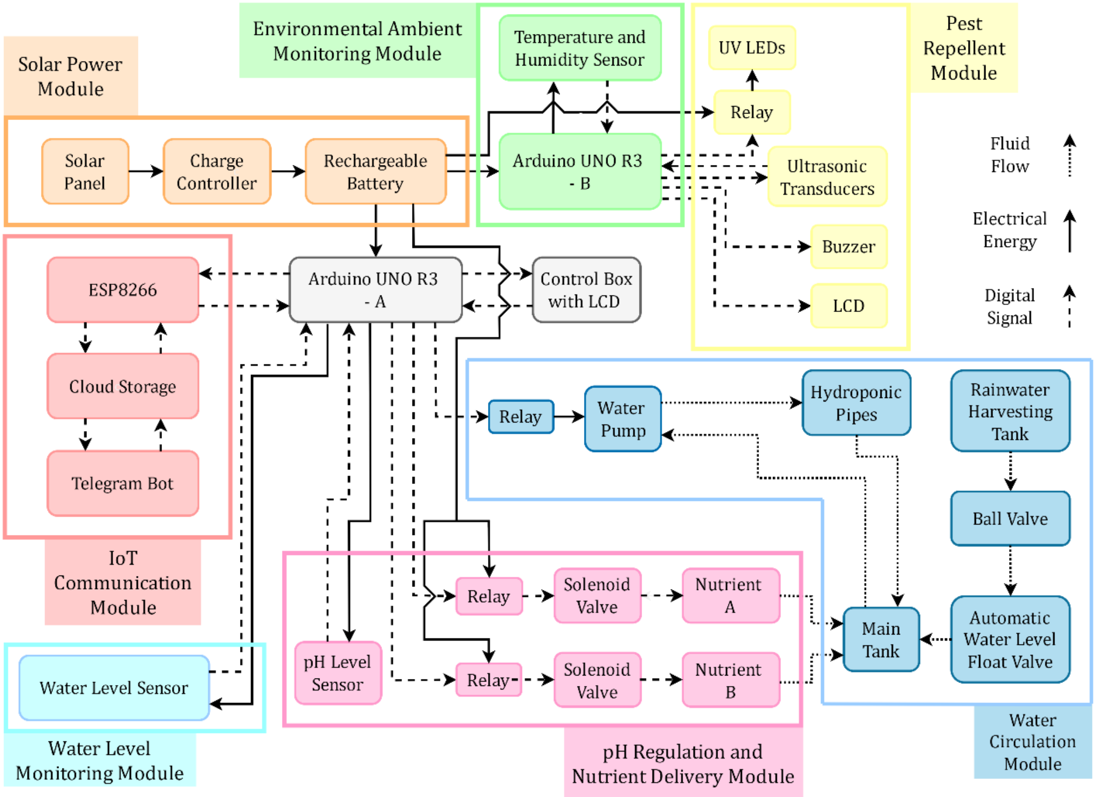


Figure 9: Functional module structure of the Off-Grid Smart Hydroponic System.

4.4 Morphological Chart

To systematically generate and evaluate multiple design possibilities, a morphological chart was constructed focusing on four core functions of the Off-Grid Smart Hydroponic System, which are solar energy generation, nutrient delivery, pH sensing, and structural framing. For each function, three technically viable options were identified, considering factors such as performance efficiency, local availability, cost-effectiveness, and compatibility with MASDAR's rural operational constraints. This structured approach allowed the design team to visualise the functional space of the system, explore trade-offs between different technical solutions, and form candidate concepts that could later be assessed using quantitative and qualitative evaluation methods such as scoring matrices and Pugh Charts. The chart therefore, provided a clear framework to guide concept generation while ensuring that all critical system requirements, from energy efficiency to classroom usability, were systematically addressed (see Table 5).

Table 5 shows the evaluated options for each key functional subsystem. Monocrystalline solar panels were selected for their high efficiency and compact size, ensuring sufficient energy generation within limited space. Aluminium frames were preferred due to their lightweight, corrosion-resistant, and portable characteristics, supporting both structural stability and classroom mobility. While optical pH sensors offer long-term accuracy, their cost was prohibitive, so combination probes were chosen as a reliable and affordable alternative. For nutrient delivery, gravity-fed solenoids provided an optimal balance between automation, low power usage, and cost-effectiveness, compared to manual feeding or high-cost pump systems. Regarding root medium, rockwool was selected over clay pebbles and coconut coir for its superior water retention and insulation, which enhances plant growth in classroom conditions. These selections collectively informed the generation of candidate concepts for subsequent scoring and evaluation.

Table 5: Morphological Chart for Key Functional Subsystems.

Function	Option 1	Option 2	Option 3
Solar Panel Type	Monocrystalline panel [11] High efficiency Compact	Polycrystalline panel [11] Balanced cost Slightly lower efficiency	Thin-film panel [12] Flexible Good under shade
pH Sensor Type	Combination pH sensor [13] Simple Compact and cheap	Differential pH sensor [13] Accurate Durable in harsh conditions	Optical pH sensor [13] Long-term stability Light-sensitive
Nutrient Delivery Method	Gravity-fed + solenoid [14] Low power Autonomous	Hand feeding [15] Manual Simple setup	Auto dosing with pump [16] Accurate High cost
Framing Structure	Aluminium frame [17] Lightweight Corrosion resistant	Wooden frame [17] Low cost Limited weather resistance	uPVC pipe [17] Waterproof May sag under load
Root Medium	Clay pebbles [18] Aerated Reusable	Rockwool [18] Good insulation Non-biodegradable	Coconut coir [18] Sustainable High Potassium content

4.5 Concept Design

Four preliminary concepts were generated by strategically combining options from the morphological chart with functional requirements derived from user surveys and environmental constraints (see Table 6). Each concept represents a viable system architecture with trade-offs in automation, cost, complexity, and educational value. These concepts were then benchmarked using qualitative and quantitative tools, such as Pugh Charts and the Weighted Decision Matrix.

Table 6: Summary of Generated Concepts.

Concept	Key Features
1	Concept 1 features a single large tank supplying water to four vertical hydroponic pipes through a solar-powered pump. Water flows from the top to promote circulation. A rooftop solar panel provides energy and shade. Nutrients are hand-fed into the tank, with a basic pH sensor monitoring the solution. Gravity aeration supports oxygenation. (See Figure 10a)
2	Concept 2 uses a compact A-frame aluminium structure supporting eight horizontal pipes. Rainwater is collected via gutters and filtered into dual tanks. Nutrients are delivered using a gravity-fed solenoid system, while a pump handles circulation. Inline pH sensing and overflow protection improve root zone stability. Castor wheels enable mobility. (See Figure 10b)
3	Concept 3 presents a vertically stacked system with eight NFT pipes, four on each side and a single combined tank. The solar panel above powers the system and provides shade. Water is pumped through the pipes, while nutrients are manually added. A pH sensor supports basic monitoring. (See Figure 10c)
4	Concept 4 is an A-frame aluminium design with stacked pipes on both sides, a solar panel on top, and integrated LED lighting for alarm and pest deterrence. A single nutrient tank feeds a pump-driven water circuit. The system includes ambient temperature, humidity, and motion sensor for semi-autonomous operation. (See Figure 10d)

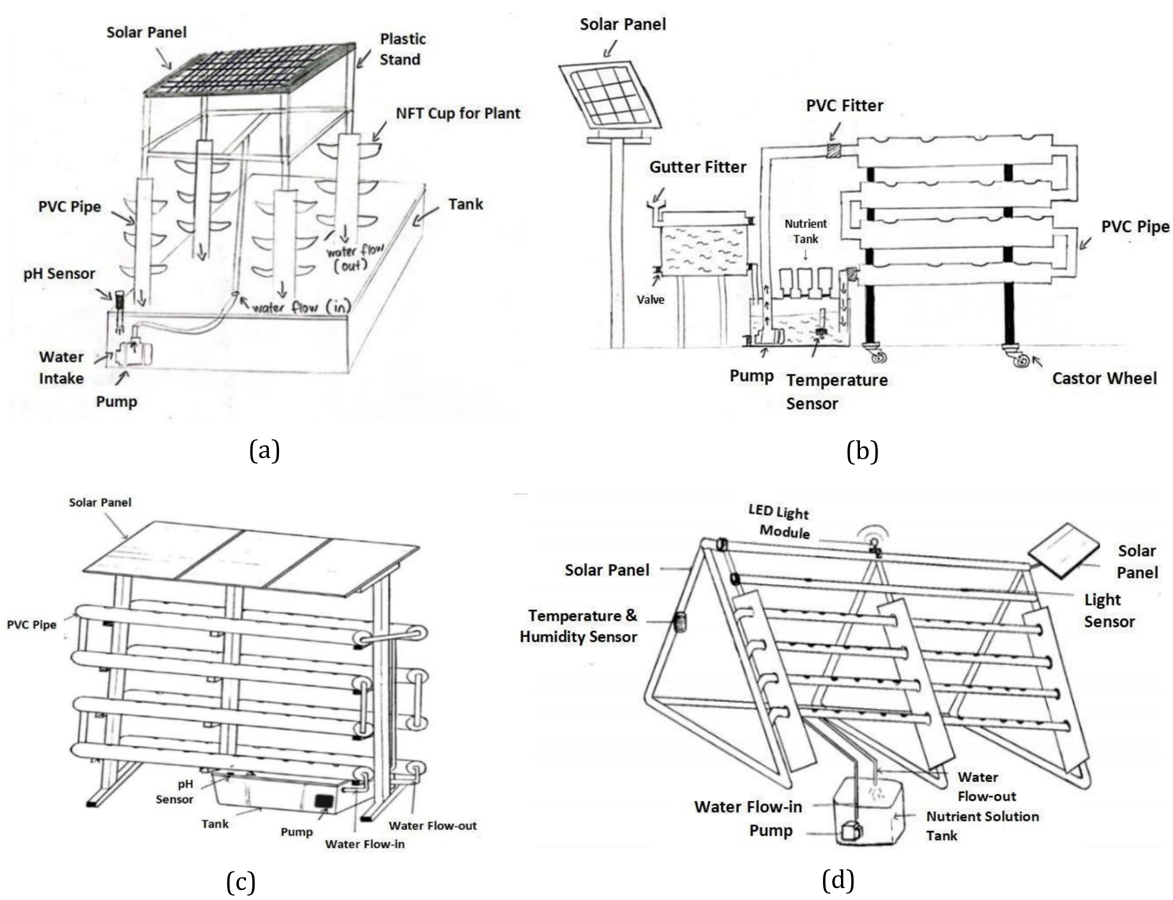


Figure 10: (a) Concept 1, (b) Concept 2, (c) Concept 3, (d) Concept 4.

The proposed Off-Grid Smart Hydroponic System distinguishes itself from existing off-grid hydroponic models through its targeted integration of solar energy, IoT-enabled monitoring, and modular, education-focused design. Unlike conventional off-grid hydroponics that primarily emphasise autonomous plant growth or energy efficiency, this system simultaneously addresses multiple under-resourced school constraints which are limited electricity, restricted water access, and minimal technical expertise while also serving as a hands-on STEM learning platform. The academic and practical gap filled by this work lies in its holistic approach where it couples renewable energy autonomy with low-cost automation, sensor-based monitoring, and portability, creating a replicable model for rural educational settings. By contextualising design choices with site-specific constraints and stakeholder feedback, the system offers an adaptable framework that advances both smart agriculture research and practical deployment in schools lacking infrastructure, bridging a critical gap between conceptual hydroponics and applied educational technology.

4.6 Design Parameters and Constraints

Final design development was driven by economic and environmental constraints relevant to MASDAR's deployment context. These parameters ensured the system's feasibility, scalability, and educational utility in real-world rural conditions.

4.6.1 Economical

Affordability was a key focus in the design of the system, especially considering the financial limitations of rural schools like MASDAR. Based on survey responses, most users expected the system to cost less than RM2000, with many preferring it to fall between RM1000 and RM1500. To meet this target, the design team followed a low-cost approach by choosing materials that are easy to find locally, such as aluminium frames and standard hydroponic parts.

Rather than using expensive industrial automation controllers, the system relies on affordable Arduino microcontrollers and low-power solenoid valves to handle automatic tasks like nutrient dosing and water flow. This kept the overall cost low without sacrificing essential features. The system was also designed in a modular way, meaning that its parts can be replaced or upgraded individually. This makes maintenance easier and cheaper, allowing teachers or students to handle repairs without needing outside help or advanced technical skills.

4.6.2 Sustainable Technology

Sustainability principles guided the system's energy, water, and material choices. Designed for full off-grid operation, the system uses solar power to maintain low daily energy consumption and avoid reliance on grid electricity. Water use is minimised through a closed-loop, gravity-assisted recirculation system, while integrated rainwater harvesting further reduces external dependency.

Nutrient dosing is automated to prevent waste, and materials were selected for durability and environmental safety. Non-toxic pest deterrents replace chemical methods, aligning with green design standards. Overall, the system supports SDGs 2 (Zero Hunger), 4 (Quality Education), and 7 (Clean Energy), serving as both a functional farming platform and an educational tool for sustainability in rural contexts [19].

Each design objective identified through the MASDAR survey and QFD analysis was systematically addressed throughout the development process. Economic and accessibility goals guided material selection and cost-effective automation using Arduino controllers and low-power solenoids. Sustainability and energy efficiency objectives informed the off-grid solar configuration, water recirculation, and automated nutrient dosing strategies. Functional and educational goals were incorporated via the morphological chart and concept synthesis, ensuring usability, modularity, and hands-on learning opportunities. Finally, insights from the survey, combined with quantitative evaluation using Pugh Charts and the Weighted Decision Matrix, confirmed that the selected concept aligns with both user needs and site-specific constraints.

5. CONCEPTUAL DESIGN

This section presents a structured evaluation of four hydroponic design alternatives, leading to the final selection of the most technically and contextually suitable concept for off-grid deployment at MASDAR. The decision-making framework integrates engineering requirements derived from prior analyses, including QFD, site-specific constraints, and stakeholder input. By applying the Pugh Chart and Weighted Decision Matrix (WDM) methods, the evaluation ensures objectivity and traceability, enabling a robust selection based on technical performance, user priorities, and deployment feasibility.

5.1 Decision Making

The design selection process followed a hierarchical and multi-criteria decision-making framework aligned with engineering design best practices. Initially, a comprehensive list of evaluation criteria was established based on customer and technical requirements synthesized from section 2. Each concept was benchmarked qualitatively using Pugh Chart analyses to eliminate inferior options and identify leading candidates. This was followed by a Weighted Decision Matrix, where numerical scores are adjusted for criteria importance which enabled a final comparative evaluation. This structured approach ensured that the selected design is aligned not only with performance metrics but also with MASDAR's operational constraints, sustainability objectives, and educational use cases.

5.2 Pugh Chart

The Pugh method was used as a qualitative screening mechanism to facilitate early-stage concept elimination based on relative performance against a reference design. Each concept was compared to a designated datum across twelve engineering characteristics, reflecting both technical and user-based considerations. The use of qualitative symbols (+, S, -) allows for structured judgment without requiring absolute values, thus supporting early decision-making when exact numerical data are limited.

5.2.1 Pugh Chart 1

Table 7 shows the first Pugh Chart iteration involving all four concepts. Concept 3 was chosen as the datum for its balanced performance. Concept 2 scored highest, excelling in sensor resolution, nutrient delivery accuracy, and filtration efficiency. Concepts 1 and 4 had some strengths but underperformed in weather resistance, water retention, and mobility. Scoring was based on expert judgment, preliminary testing, and stakeholder input.

Table 7: Pugh Chart 1 Evaluation of Conceptual Designs Relative to Datum (Concept 3).

Engineering Characteristics	Concept 3	Concept 1	Concept 2	Concept 4
Size		+	-	+
Price		S	+	+
Power Consumption		+	-	S
Weight		-	+	+
Mobility		S	+	S
Water Storage		+	+	-
Weather Resistance	DATUM	+	+	S
Maintenance Time		-	+	S
Water Retention Capacity		-	S	S
Filtration Efficiency		+	+	S
Precision & Accuracy of Nutrient Delivery		S	+	S
Sensor Resolution		S	+	+
Number of Plusses (+)	0	5	9	4
Number of Minuses (-)	0	3	2	1
Rank	**4**	**3**	**1**	**2**

5.2.2 Pugh Chart 2

To confirm the robustness of the first iteration, a second Pugh Chart was developed, now restricted to the three highest-ranked concepts (See Table 8). In this comparison, Concept 2 continued to demonstrate superior performance in multiple high-impact domains. Although Concept 1 and Concept 4 exhibited comparable results, neither provided a compelling advantage in terms of overall system viability. This reinforced the selection of Concept 2 as the leading design option.

The results from both Pugh Chart iterations collectively affirm that Concept 2 consistently meets the technical, functional, and operational demands of the MASDAR deployment context more effectively than the other alternatives.

Table 8: Pugh Chart 2 Focused Comparison Among Top Concepts Relative to Datum (Concept 2).

Engineering Characteristics	Concept 2	Concept 1	Concept 4
Size	DATUM	+	+
Price		-	S
Power Consumption		S	+
Weight		+	S
Mobility		-	-
Water Storage		S	-
Weather Resistance		S	-
Maintenance Time		+	+
Water Retention Capacity		-	S
Filtration Efficiency		S	-
Precision & Accuracy of Nutrient Delivery		-	-
Sensor Resolution		-	S
Number of Plusses (+)	0	3	3
Number of Minuses (-)	0	5	5
Rank	**1**	**2**	**2**

5.3 Weighted Decision Matrix

The Weighted Decision Matrix (WDM) provided a quantitative foundation for final design selection by assigning numerical values to each concept based on its performance against predefined evaluation criteria [20]. The weightage for each criterion was derived from the Objectives Tree (Section 5.3.1), which in turn reflects insights from the MASDAR user survey, team discussions, and consultation with academic supervisors. This methodology enabled an analytically rigorous comparison of competing concepts across twelve distinct criteria.

5.3.1 Objectives Trees

The Objectives Tree presented in Figure 11 outlines the hierarchical decomposition of design priorities for the Off-Grid Smart Hydroponics system. This structure groups system requirements into five main categories, which are Functional Efficiency, Water Management, Physical Characteristics, Maintenance and Monitoring, and Cost Consideration. Each primary function is broken into sub-criteria with normalized weights that collectively sum to 1.0, enabling objective score aggregation in the WDM.

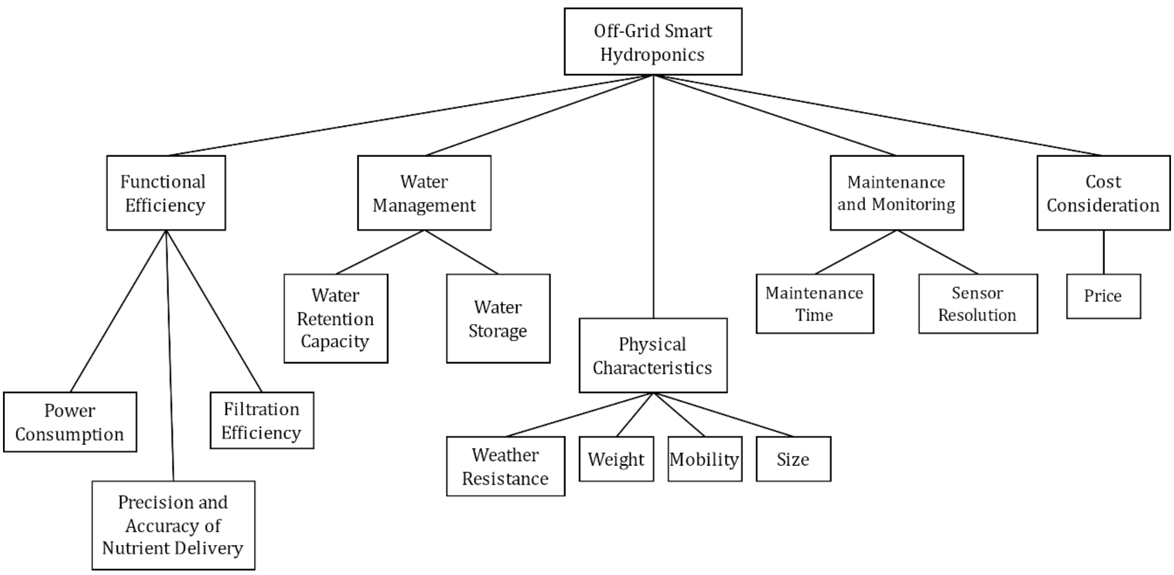


Figure 11: Functional Objectives Tree for Off-Grid Smart Hydroponics System.

Functional Efficiency, weighted at 0.20, covers energy performance and nutrient control, comprising sub-weights of 0.06 for power consumption, 0.06 for filtration efficiency, and 0.08 for precision in nutrient delivery. Water Management also holds a 0.20 weight, divided into water retention (0.06) and storage capacity (0.07), aligning with off-grid requirements.

Physical Characteristics, weighted similarly at 0.20, includes weather resistance (0.07), structural weight (0.08), mobility (0.05), and size (0.07), reflecting portability and deployment adaptability. Maintenance and Monitoring, at 0.10, emphasizes usability through maintenance time (0.06) and sensor resolution (0.04), both critical for system longevity and feedback accuracy.

Cost Consideration, the highest weighted at 0.30, reflects economic feasibility, especially for rural or educational implementation. The price sub-factor carries the full 0.30 weight, given its impact on system scalability and user adoption. These values are consolidated in Figure 12, providing a quantitative reference that enables consistent, criteria-based design evaluation in the following decision-making section.

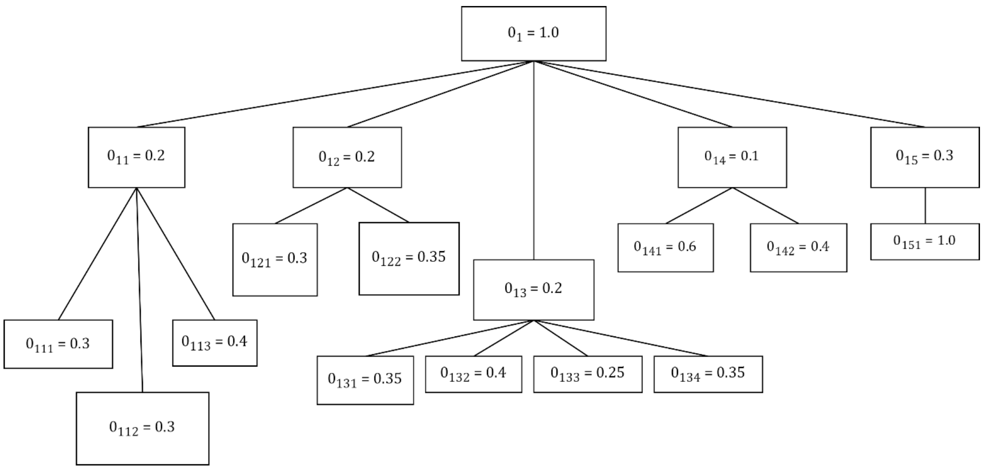


Figure 12: Normalized Weightage Assignment for Functional Objectives.

5.3.2 Scoring the Design Alternatives

The Weighted Decision Matrix (Table 9) evaluated each concept using an 11-point Likert scale (0 = totally inadequate, 10 = ideal), allowing detailed assessment of how well each design met its criteria. Scores were assigned based on MASDAR site evaluations, consultations with academic supervisors and structured user survey input. Raw scores were multiplied by the weightings from Section 5.3.1 to produce normalized values, and the sum of these weighted scores provided each concept's total viability. This procedure ensured that all evaluation criteria contributed proportionally, aligning technical selection with both user requirements and site-specific constraints.

Table 9: Weighted Decision Matrix for Off-Grid Smart Hydroponic Design Alternatives.

Design Criterion	Weight	Unit	Concept 1	Score	Concept 2	Score	Concept 3	Score	Concept 4	Score
Price	1	RM	High (5)	5	Fair (8)	8	High (5)	5	Fair (8)	8
Size	0.35	m^2	Compact (6)	2.1	Large (5)	1.75	Medium (7)	2.45	Compact (8)	2.8
Power Consumption	0.3	Watt	High (5)	1.5	High (5)	1.5	High (5)	1.5	Moderate (6)	1.8
Water Storage	0.35	Liter	High (7)	2.45	High (8)	2.8	Moderate (5)	1.75	Low (4)	1.4
Weight	0.4	Kg	Light (7)	2.8	Heavy (3)	1.2	Moderate (5)	2	Heavy (3)	1.2
Maintenance Time	0.6	Hour	Low (7)	4.2	High (3)	1.8	Moderate (5)	3	Moderate (5)	3
Sensor Resolution	0.4	xx.xx	Moderate (4)	1.6	High (8)	3.2	Moderate (4)	1.6	High (6)	2.4
Water Retention Capacity	0.3	n/a	High (6)	1.8	Moderate (5)	1.5	Moderate (5)	1.5	Moderate (5)	1.5
Filtration Efficiency	0.4	n/a	Moderate (4)	1.6	Moderate (8)	3.2	Low (4)	1.6	Low (4)	1.6
Precision & Accuracy of Nutrient Delivery	0.3	n/a	Moderate (5)	1.5	High (8)	2.4	Moderate (5)	1.5	Moderate (5)	1.5
Weather Resistance	0.35	n/a	High (6)	2.1	High (8)	2.8	Low (4)	1.4	Low (5)	1.75
Mobility	0.25	n/a	Adjustable (4)	1	Portable (8)	2	Adjustable (4)	1	Adjustable (5)	1.25
			Total Score	**27.7**		**32.2**		**24.3**		**28.2**
			Ranking	**3**		**1**		**4**		**2**

5.4 Selected Design Concept

Following a comprehensive comparative assessment using both qualitative and quantitative methods, Concept 2, an NFT (Nutrient Film Technique) based system, was selected as the final design. Concept 2 consistently ranked highest across all evaluation methods, especially in filtration efficiency, sensor resolution, nutrient delivery accuracy, and weather resistance. These characteristics directly support autonomous, low-maintenance operations, which are essential for off-grid deployments.

Although Concept 2 is comparatively heavier than the other alternatives, this trade-off is justified by its improved performance and system stability. The NFT architecture facilitates continuous nutrient circulation and supports seamless integration with renewable power sources and IoT-based monitoring systems. Its modularity and design simplicity make it cost-effective and scalable, aligning well with MASDAR's goals of sustainability, educational impact, and infrastructure independence. This selection reflects a design that is technically sound, economically viable, and tailored to the user and site-specific needs identified throughout the project.

6. CONCLUSION

This paper presented the conceptual foundation and preliminary design framework for an Off-Grid Smart Hydroponic System developed under the SULAM initiative at Maahad Tahfiz Sains Darul Muttaqin (MASDAR). Through structured need analysis, market surveys, and engineering design tools such as QFD and the Weighted Decision Matrix, the study identified user requirements and translated them into a technically feasible and contextually relevant solution. The selected Nutrient Film Technique (NFT)-based design, supported by solar energy and IoT-enabled automation, directly addresses infrastructural constraints such as limited electricity and water access, while simultaneously providing an educational platform for STEM learning.

In relation to the stated objectives, the study, (i) introduced the concept of an IoT-integrated solar hydroponic system within a school environment as a platform for STEM-based learning, (ii) incorporated sensors for pH and temperature as part of the conceptual design in line with Malaysia's IR 4.0 agenda, (iii) demonstrated the potential for cost savings by enabling vegetable cultivation through an autonomous solar-powered setup, (iv) embedded real-time pH monitoring and automated dosing into the functional design, (v) promoted sustainability by integrating renewable energy with rainwater harvesting for irrigation, and (vi) proposed a portable, modular frame structure that supports classroom mobility and adaptability. These objectives were conceptually fulfilled in this phase, while their technical realization and validation are reserved for Part 2 of the study.

The findings underscore that integrating renewable energy with smart agriculture can yield practical, low-maintenance, and sustainable farming solutions for under-resourced environments. Beyond its technical contributions, the project demonstrates the potential of hydroponics as both a source of food security and a pedagogical tool that promotes digital literacy, sustainability awareness, and hands-on engineering experience among students. Looking ahead, Part 2 of this journal will extend the work by detailing the design configuration, technical analysis, and prototyping process, providing empirical validation of the proposed system and further insights into its performance and scalability.

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