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Research

Design and experimental analysis of a closed-loop autonomous rotary hydroponics system for revolutionizing fenugreek yield and enhancing food security

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Abstract
The rotary hydroponics system offers a space-saving and potentially high-yielding solution for soilless cultivation, promoting efficient resource use and automation for sustainable food production. This research investigates a closed-loop rotary hydroponics system designed to revolutionize fenugreek yield and enhance food security through resource-efficient and automated cultivation. Building upon the established benefits of aeroponics, particularly its efficient use of space and resources, rotary hydroponics introduces a groundbreaking, cylindrical design. This innovative approach not only maximizes space efficiency but also paves the way for further automation within the cultivation process. The proposed study delves into the design, development, and experimental analysis of a closed-loop, self-sustaining, and low-maintenance rotary hydroponics system specifically designed for fenugreek cultivation. The system prioritizes minimal human intervention through the integration of software-controlled monitoring and parameter adjustments. The research investigates the effectiveness of the system in promoting plant growth and analyzes the growth stages of fenugreek seedlings transplanted into the system. The experiment yielded promising results, with fenugreek plants reaching full maturity within 30 days and achieving an average height of 15–20 cm. These findings highlight the potential of the rotary hydroponics system to revolutionize fenugreek yield and bolster food security through its resource-efficient and sustainable cultivation approach.

Keywords Automated nutrient delivery · Closed-loop system · Fenugreek yield enhancement · Resource-efficient cultivation · Rotary hydroponics system · Sensor-based monitoring · Vertical farming

1 Introduction

The agricultural sector, the cornerstone of human civilization, faces an unprecedented confluence of environmental and logistical threats. Climate change disrupts weather patterns, jeopardizing crop yields [1, 2]. Arable land, the lifeblood of traditional farming, is steadily shrinking due to urbanization and desertification [3]. Additionally, a growing shortage of agricultural labor hinders production capacity [2, 4]. These interconnected challenges pose a significant risk to global food security, demanding a fundamental transformation of agricultural practices.

This critical juncture necessitates the exploration of innovative and sustainable solutions that not only guarantee a stable food supply but also operate within the constraints of a rapidly changing environment [5]. Soilless farming

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techniques like hydroponics offer a promising alternative to traditional soil-based methods [6–8]. Hydroponics eliminates the limitations of soil, promoting accelerated plant growth rates, enhanced yields, and significantly reduced water consumption [9, 10]. Notably, aeroponics, a specific type of hydroponics that suspends plant roots in a controlled mist environment, offers even greater efficiency and resource optimization [6, 11, 12]. However, existing hydroponics systems can be limited by spatial constraints and may necessitate specific growth mediums [11, 13].

Building upon the well-established foundation of hydroponics research, this investigation delves into a specific advancement: rotary hydroponics [14]. While hydroponics has emerged as a promising solution to address water scarcity and food security challenges, limitations such as spatial constraints and the requirement for specific growing mediums remain [15]. Extensive research efforts have been directed towards optimizing hydroponics for indoor cultivation, exploring advancements in vertical farming, LED technology integration, and automation through the Internet of Things (IoT) and fuzzy logic control [16–18]. The present study leverages these established advancements by focusing on a novel rotary hydroponics system. This system is designed to specifically address the spatial limitations inherent in traditional hydroponics, while simultaneously incorporating automation features to facilitate efficient and resource-optimized cultivation [14, 19].

Extensive research efforts have explored various aspects of hydroponics, paving the way for its continued development and optimization. Friero et al. [20] investigated the impact of temperature on young maize seedlings grown hydroponically. Their study revealed that temperature significantly affects root growth rates and DNA replication within the root zone [21]. This research contributes to a deeper understanding of temperature regulation in hydroponics and its influence on plant development. Vertical farming (VF) has emerged as a promising solution to address the rising global demand for food. By utilizing vacant spaces in urban areas, VF offers the potential to increase food production while reducing pressure on traditional agricultural land [22, 23]. Additionally, VF can mitigate the negative effects of climate change on food production and ensure the preservation of food quality and nutritional value. Making hydroponics accessible to small-scale farmers, particularly those in developing regions, is crucial for widespread adoption. S Pawar et al., [16] present a project focused on creating a cost-effective vertical hydroponics system for Indian farmers. The study highlights the development of a low-cost pH module, effectively reducing financial barriers for farmers interested in hydroponics. Table 1 provides a detailed comparison of various aeroponics, and hydroponics systems based on key criteria analyzed in the reviewed research papers.

1.1 Challenges in rotary hydroponics system

Hydroponics systems, while offering advantages such as increased growth rates and efficient nutrient delivery, also present certain obstacles that constrain their widespread adoption [27–29]. A significant challenge is the high initial cost associated with installation and operation [30]. Hydroponics systems necessitate misting systems, sensors, and environmental controls, all of which can be expensive. Moreover, maintaining a sterile environment and achieving precise nutrient management are critical for preventing disease outbreaks and ensuring optimal plant growth [6, 11]. These factors necessitate a high level of technical expertise, which can be a barrier for some potential users. Figure 1 depicts the key challenges associated with rotary hydroponics, which includes substantial upfront investment due to the specialized components required (misting systems, sensors, rotating apparatus). In addition, effective operation necessitates technical expertise for system control, nutrient monitoring, and maintaining optimal growth conditions.

This research explores a transformative innovation in soilless cultivation: rotary hydroponics. Building upon the well-established advantages of aeroponics, particularly its efficient use of space and resources, rotary hydroponics introduces a groundbreaking cylindrical design. This design not only maximizes spatial utilization but also lays the groundwork for further automation within the cultivation process [30, 31]. This study presents the design, development, and implementation of a novel closed-loop rotary hydroponics system specifically engineered for minimal human intervention. The system achieves this through the integration of software-controlled monitoring and automated parameter adjustments, ultimately promoting optimized cultivation conditions. This investigation will evaluate the compact and spatially optimized design of rotary hydroponics system, directly addressing a critical constraint associated with conventional hydroponics configurations [27]. By overcoming these limitations, rotary hydroponics presents a transformative technology with the potential to revolutionize agricultural practices [28]. This innovation holds promise for enhancing global food security through the implementation of resource-efficient and sustainable production methods across diverse geographical locations [32]. Also, the design of the system contributes to a reduced environmental footprint by minimizing water consumption and optimizing resource utilization. Furthermore,

Table 1 Comparison of different soilless systems

Sr. No	Soilless System	Description	Advantages	Limitations	Refs
1	Hydroponics	Sources of nutrient elements with their characteristics	pH of various vegetable species	Root dipping technique, floating technique	[24]
2	Multi-tier cylindrical hydroponics	Multi-tier cylindrical hydroponics system as a possible vertical farming	Tight-spaced high-rise buildings with improved productivity over the rotary system	LEDs and plant growth	[25]
3	Vertical aeroponics	Plants are grown in tall towers, with nutrient mist sprayed on a regular basis	Space-efficient, scalable vertically	Maintenance challenges, potential for uneven nutrient distribution	[23]
4	Hydroponics: nutrient film technique (NFT)	A thin layer of nutrient solution flows constantly over plant roots	Efficient nutrient delivery, uses less water	Prone to clogging, dependent on continuous flow	[14]
5	Aeroponics fog system	A fine mist of nutrients solution is sprayed or fogged continually around plant roots	Excellent oxygenation, increased nutrient absorption	Technical complexity	[26]

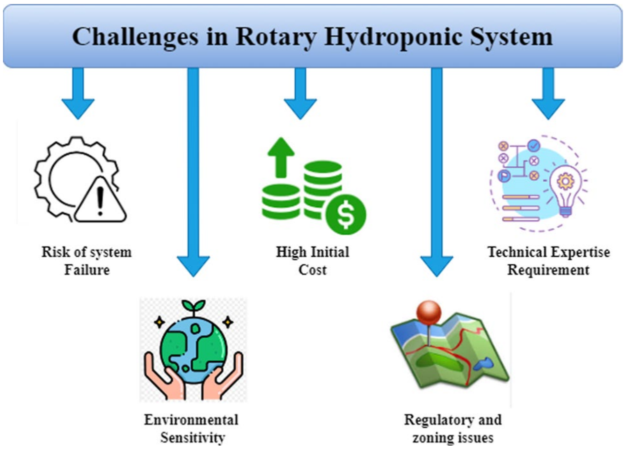


Fig. 1 Challenges in rotary hydroponics system

rotary hydroponics fosters improved accessibility for individuals and communities seeking fresh, locally grown produce due to its potential for decentralized and space-conscious cultivation.

2 Methodology

This research employed a two-part design methodology to develop an automated plant growth system. The first phase concentrated on the User Interface (UI) design, ensuring seamless interaction and control. This stage commenced with selection of functionalities and features of the automation system were meticulously determined. This involved discerning which aspects of plant growth would be automated, such as establishing watering schedules or light cycles crucial for plant health. Finally, the logic governing the operation of system was meticulously developed. This entailed specifying the rules and conditions that would guide the actions of system, like setting watering schedules based on data collected from sensors monitoring moisture levels [24].

The second phase centered on designing the model, which encompassed the physical construction of the automated growth system. Here, the project commenced with selecting appropriate materials that would best serve the functionality and durability of system. These materials underwent rigorous testing to ensure their suitability for the intended purpose. This testing likely involved checking for durability, compatibility with other materials the plants would interact with (e.g., ensuring pipes wouldn't leach harmful chemicals), and overall suitability for creating a nurturing environment for the plants. Finally, this work adopted a stage-wise development approach [24, 33]. This likely involved breaking down the construction of the automated plant growth system into smaller, more manageable tasks that could be completed sequentially. Following the completion of the UI design and the physical model design, the project culminated in transferring plants to the automated system for their cultivation, allowing us to evaluate the effectiveness of the designed system [34]. Figure 2 illustrates a meticulously designed various process for developing a hydroponic growing system equipped with automation functionalities. This approach fosters a systematic and controlled environment, ultimately optimizing the success of the automated hydroponic growing system. Figure 3 presents a meticulously designed, various process for developing electronic products. Initiating with material selection, the process progresses through hardware and electronic component selection, culminating in the creation of a detailed circuit diagram. Subsequent stages involve material arrangement and final assembly, resulting in the complete product. The process concludes with preparing a designated environment for testing or product use.

In this study, the growth of fenugreek plants within the rotary hydroponics system was evaluated through continuous monitoring of key parameters across three distinct stages: establishment, vegetative growth, and maturity. Following transplantation, seedlings received a customized nutrient solution. Plant growth was meticulously monitored, with adjustments made to the nutrient concentration based on these observations. Plant height served as the primary growth parameter, meticulously measured throughout the experiment to quantify growth trajectory of the fenugreek plants.

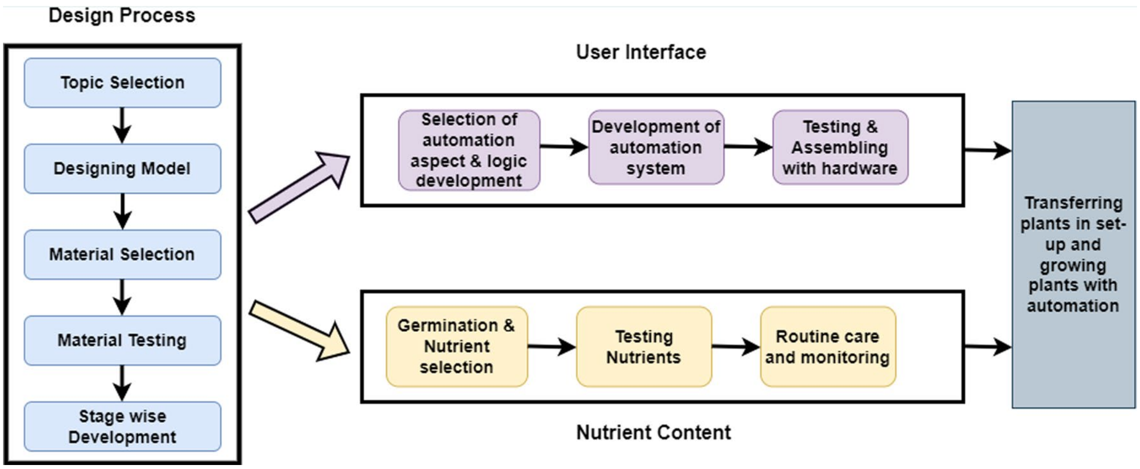


Fig. 2 Design process for a hydroponic growing system with automation

Fig. 3 Product development process with material selection and electronics integration

3 Design and development

3.1 Design process and selection of components

The research aimed to develop a novel rotary hydroponics system that addresses limitations of spatial constraints and enhances resource efficiency. The core structure of system is a cylindrical metal frame mounted on a wheeled metal stand for mobility. A central shaft connected to a motor enables the rotation of cylindrical frame, providing for uniform plant exposure to light and nutrients. An integrated galvanized steel tray positioned below the frame captures excess solution.

3.2 Design considerations

The design of the rotary hydroponics system prioritizes maximizing plant growth potential within a space-constrained environment. The core structure features a cylindrical metal frame mounted on a wheeled metal stand for effortless maneuverability. The stand is constructed from robust metal rods to ensure stability and facilitate system relocation. A central shaft connected to a motor enables the cylindrical frame's rotation, providing for uniform plant exposure. An integrated galvanized steel tray positioned below the frame captures excess nutrient solution.

Within the cylindrical frame, two metal rings fabricated from a suitably bendable material with high yield strength serve as the foundation for plant growth. These rings are equipped with multiple PVC pipes strategically selected for optimal nutrient flow. Each pipe segment functions as an individual housing unit for the plants, secured to the rings using clamps. The PVC material offers a lightweight, durable, and cost-effective solution for nutrient delivery [35]. To facilitate efficient nutrient uptake, small holes are drilled strategically within the pipes, and 3 cm slits are incorporated to enhance growing conditions. The cylindrical design optimizes space utilization by allowing for the placement of multiple growth stations within the rotating frame. The growth stations are the designated areas within the cylindrical design where plants or other organisms can be cultivated or grown. These stations are essentially compartments or sections within the structure where specific environmental conditions such as lighting, temperature, humidity, and nutrient supply can be controlled and optimized for the growth of desired plants or organisms. This design feature facilitates efficient use of space while enabling multiple cultivation experiments or activities to occur simultaneously within the rotating frame.

3.3 Material selection

This meticulously crafted design prioritizes both spatial efficiency and resource optimization. The selection of galvanized steel (GI) for the tray minimizes the risk of corrosion while remaining cost-effective compared to stainless steel alternatives. The rotating mechanism ensures equitable distribution of light (provided by an LED grow light mounted on the shaft) and nutrient solution (delivered when the plants meet the tray during rotation). This design approach fosters a controlled and productive environment for optimal plant growth.

3.4 Overall specifications for rotary hydroponics system

The hydroponics system consisted of a cylindrical structure constructed from GI due to its cost-effectiveness and resistance to corrosion compared to other materials. The structure comprised two welded metal rings, each with a 30 cm radius, connected by three 30 cm metal pipes welded along a central shaft. The shaft was mounted on a stand of appropriate height, incorporating a bearing for rotation and a wheeled base for mobility. For optimized space utilization and plant capacity, the cylindrical design employed 63 mm diameter pipes segmented and attached to the rings using clamps. These segments facilitated nutrient flow through strategically drilled holes and a 3 cm slit incorporated for enhanced growing conditions. A motor connected to the shaft rotated the system at a controlled rate of 2 rpm to 3 rpm, ensuring consistent plant exposure to nutrient solution via a tray positioned below. Additionally, an LED grow light mounted on the shaft provided the necessary light spectrum for optimal plant growth. Figure 4 presents a comparative view of a rotary hydroponics system in both its digital and physical form. Figure 4(a) depicts a computer-aided design (CAD) model, which offers a detailed blueprint of layout of the system. This includes the

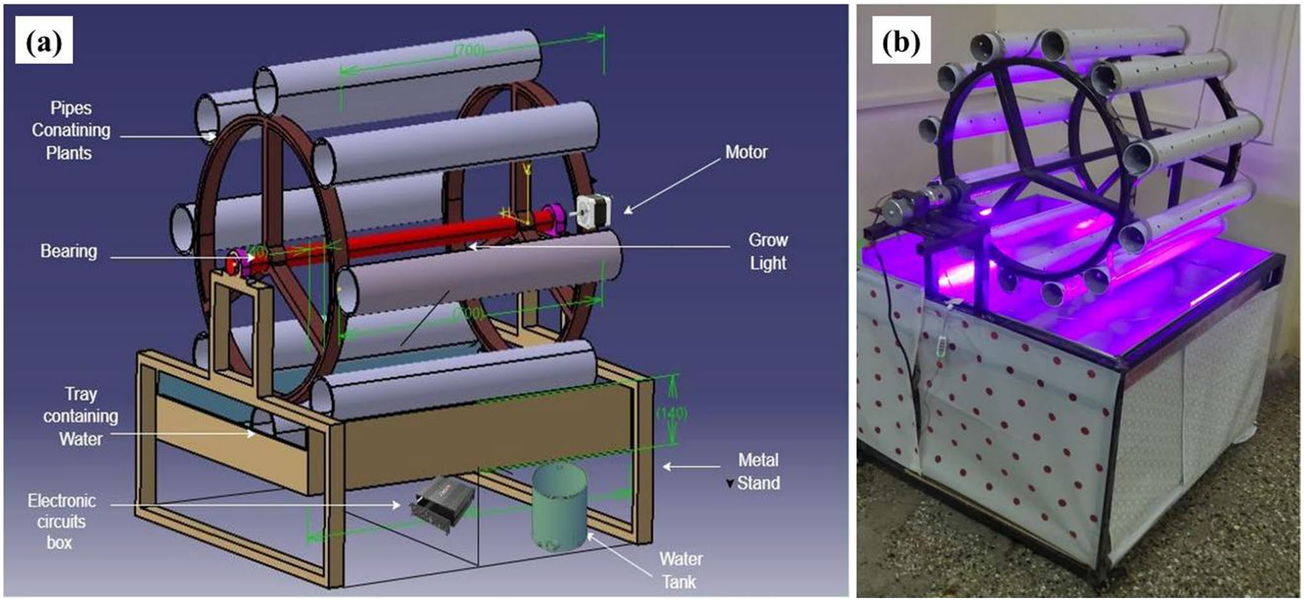


Fig. 4 Rotary hydroponics system **a** CAD model **b** Actual model

core cylindrical frame, the rotating rings that will house the plants, and all other essential components. Figure 4(b) showcases a photograph of the actual, functioning hydroponics system.

The automated growth setup is a cylindrical structure that rotates for even exposure. Plants are positioned within cups located on pipes inside this structure. A network of pipes delivers nutrient water from a reservoir to the plants. This reservoir system is a key aspect of the automation. One tank holds regular water, while another contains essential nutrients like NPK, calcium nitrate, magnesium, and sulphates. Water from the first tank is mixed with the nutrients in a final tank at a rate of 3–5 ml per liter. The resulting solution is then tested to ensure it meets the desired pH and TDS levels. If these levels are within the acceptable range, the nutrient water is transferred to the tray for delivery to the plants. An error message is displayed if adjustments are needed. The rotating cylindrical structure ensures even distribution of the nutrient water, which reaches the roots of plants through openings in the PVC pipes and the Oasis cube material. Additionally, a grow light mounted on the shaft provides necessary light for plant growth, while an automatic cooling fan maintains a stable temperature within the entire setup.

3.5 Automated control and monitoring

The hydroponics system incorporates an automated control and monitoring system for optimal plant growth. This system is divided into two primary functions: environmental control and nutrient solution monitoring.

3.6 Environmental control

The hydroponics system is controlled by a central microcontroller unit, specifically the NodeMCU ESP32. This device, equipped with a Tensilica LX6 Dual-Core processor running at a clock frequency of 240 MHz, manages water flow and motor operation. With 512 kB of SRAM and 4 MB of memory, it transmits control signals to a relay, serving as a power supply switch for various components. These include the elove 24 V submersible pump, known for its 40-Watt power and maximum flow rate of 3200 Liters Per Hour, as well as the AC motor and 12 V pump, commonly used for rotating mechanisms and nutrient delivery or water circulation, respectively. The ESP-32 governs the operation of these components based on pre-defined parameters, ensuring precise control over water flow and motor activity, and ultimately maintaining optimal environmental conditions within the hydroponics system.

3.7 Nutrient solution monitoring

The second section focuses on continuously monitoring the quality of the nutrient solution. The system is equipped with various sensors and actuators, including a pH sensor and a total dissolved solids (TDS) meter. The pH sensor is utilized to assess the quality of water or nutrient solutions by measuring their acidity or alkalinity levels. This allows growers to identify impurities and maintain proper nutrient balance for optimal plant growth. Meanwhile, the TDS meter enables precise measurement of nutrient concentration in the water, facilitating adjustments to ensure the health and vitality of the plants. An OLED display is incorporated into the system to provide real-time monitoring and visualization of critical parameters. This display technology offers clear and vibrant visuals without the need for a separate backlight, enhancing user interface and interaction with the hydroponics system.

3.8 Remote monitoring

The system can be optionally expanded to include remote monitoring capabilities. An ESP32 Camera module with a Wi-Fi antenna can be integrated to transmit digital video feeds to the *Blynk app*. This allows users to remotely monitor plant growth within the hydroponics system for added convenience. To control high-voltage and high-current loads, a relay module is employed, allowing the microcontroller to switch these components ON and OFF as needed. This ensures safe and efficient operation of the system while providing flexibility in controlling various elements. Also, the ESP8266 microchip is utilized for wireless communication, enabling connectivity and data exchange with other devices or networks. With built-in Wi-Fi capability and microcontroller functionality, the ESP8266 facilitates seamless integration into IoT projects, enhancing the versatility and accessibility of the system. Figure 5 showcases the Blynk user interface, a revolutionary mobile application designed for remote management of an IoT-integrated system. This intuitive interface empowers users to control various aspects of the system through their smartphones. Figure 5a, b, and c all represents user interfaces designed to control an automation system via "ON" and "OFF" buttons. However, these interfaces exhibit variations in their layout.

4 Results and discussion

The initial 18–20 days are dedicated to seed germination and early plant growth within a nursery. Seeds are sown in Oasis cubes, a supportive and moisture-retaining medium. To ensure proper nourishment, a nutrient solution with a concentration of 2 ml per liter is provided every 2 days. The pH and TDS levels of this solution are monitored and adjusted to maintain a range of 5.5 to 6.5 for pH and 400 ppm for TDS, which is optimal for plant health. After this initial growth period, the young plants are ready to be transferred to the automated growth setup. Figure 6 illustrates the germination and early growth stages of fenugreek seedlings in a nursery environment before their transfer to the main hydroponics system. Figure 6(a) portrays a nursery tray containing a homogenous bed of germination cubes. These cubes, crafted from a moisture-retentive sponge-like material, serve a crucial role in supporting the germinating seeds and fostering

Fig. 5 Blynk User—Interface for controlling the Automation System

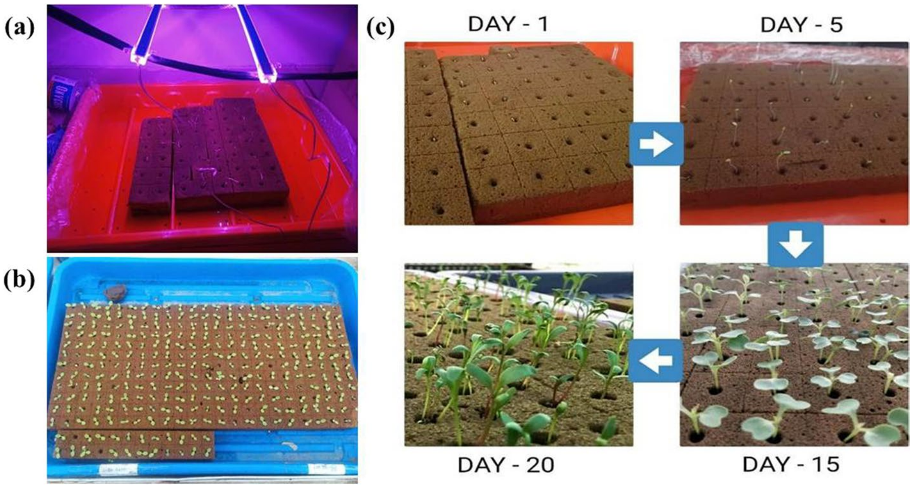


Fig. 6 **a** Nursery Set-up of day-1; **b** Nursery set-up of day-5; **c** Various stages of the fenugreek growth at day 1, 5, 15 and 20

optimal early growth conditions. Within each cube, a single fenugreek seed has been meticulously sown. Figure 6(b) presents the nursery tray 5 days after the initial seeding process. By this stage, germination would have likely commenced, with the emergence of small radicles (primary roots) and possibly even cotyledons (seed leaves) from some of the cubes. Figure 6(c) illustrates the progressive growth trajectory of the fenugreek seedlings throughout the nursery stage at days 1, 5, 15, and 20. By day 15, the seedlings would have experienced significant growth compared to day 5. They likely possess well-developed true leaves alongside an increased stem length. Day 20 marks a stage of further growth for the fenugreek plants. They would have established a more robust root system and possess several true leaves, signifying their readiness for transplantation into the permanent rotary hydroponics system.

4.1 Growth stages and observations

The experiment monitored plant growth through three distinct stages, each characterized by specific observations and adjustments to the nutrient regimen:

4.2 Establishment and nutrient application

The experiment commenced with the establishment of the plants within the hydroponics system (Figures 6, 7a). Seedlings measuring approximately 6–7 cm in height were meticulously transplanted and strategically spaced at 15 cm intervals to optimize their growth potential. A custom-designed nutrient solution, formulated to provide essential elements for plant development, was administered daily at a rate of 100 ml per liter of water. This solution included vital macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), supplemented by calcium (Ca) and magnesium (Mg). A rotating mechanism operating at 5 rpm ensured uniform distribution of the nutrient solution throughout the system, fostering optimal growing conditions for the young plants.

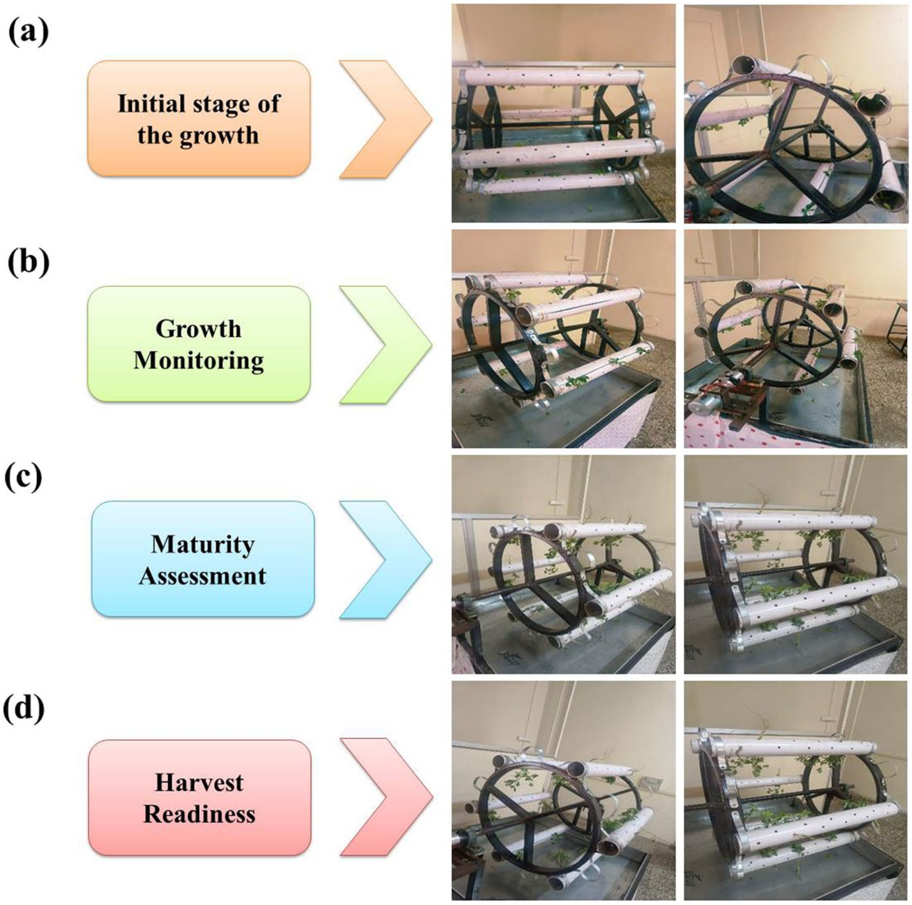
4.3 Growth monitoring and nutrient adjustment

Following a 15 day acclimation period within the hydroponics environment (Figure 7b), fenugreek plants exhibited a substantial growth spurt, attaining an average height range of approximately 10–12 cm. To cater to the correspondingly heightened nutritional demands of these maturing plants, the nutrient solution concentration was strategically adjusted by an additional 100 ml per liter of water.

4.4 Maturity assessment

The fenugreek plants continued their impressive growth trajectory even after transplantation. By day 20, with the adjusted nutrient concentration of 100 ml per liter (Figure. 7c), they had reached an average height range of 12–15 cm. This progress culminated in full maturity by day 30, with plants averaging a height of 15–20 cm (Figure 7d). Reaching

Fig. 7 Fenugreek growth monitoring and assessment



this definitive growth stage marked the fenugreek as ready for harvest, signifying successful cultivation capabilities of the system.

4.5 Nutrient management

A specially formulated hydroponics nutrient solution was employed throughout the experiment to ensure optimal plant growth. This solution comprised two distinct types of mineral supplements provided in varying quantities throughout the growth cycle, as detailed in Table 2. The table outlines the weekly administration schedule for the nutrient solution, specifying the precise quantities of N, P, K, and water used at each interval. Table 2 reveals a strategic manipulation of nutrient application. Nitrogen application exhibits a steady rise throughout the experiment, potentially reflecting its crucial role in vegetative growth. Conversely, potassium application follows a more nuanced pattern, reaching a peak during week three before a slight decline. This table serves as a comprehensive reference for the specific nutrient and water availability that the plants were exposed to during each stage of their growth cycle.

Table 2 Nutrient and water given to the plants

Sr. no	Duration in weeks	Nutrient-1: nitrogen (N) in ml	Nutrient-2: phosphorus (P) in ml	Nutrient-3: potassium (K) in ml	Water (Litter)
1	1st	8	6	5	4
2	2nd	15	12	10	8
3	3rd	26	20	16	10
4	4th	35	35	40	12
Total	4 weeks	84	73	71	34

This research on the rotary hydroponics system holds significant promise for promoting sustainable and secure food production. The vertical design of system maximizes space utilization, enabling cultivation in areas with limited land availability. Moreover, the efficient use of water and nutrients inherent to hydroponics minimizes resource consumption compared to traditional soil-based agriculture. Furthermore, the potential for automation within the rotary system can contribute to reduced labour requirements and increased production capacity. These factors combined can enhance food security by enabling cultivation in diverse environments and potentially increasing food production with a smaller environmental footprint.

5 Conclusion

This research on the rotary hydroponics system offers a compelling solution for addressing the pressing concerns of food security and resource scarcity. The vertical design of system maximizes space utilization, enabling cultivation in areas with limited land availability. Additionally, the inherent efficiency of hydroponics in water and nutrient usage minimizes resource consumption compared to traditional soil-based agriculture. Furthermore, the potential for automation within the rotary system can contribute to reduced labour requirements and increased production capacity. These combined factors position rotary hydroponics as a transformative technology with the potential to revolutionize agricultural practices. This innovation holds promise for enhancing global food security by enabling cultivation in diverse environments and potentially increasing food production with a smaller environmental footprint. The successful cultivation of fenugreek in this experiment serves as a strong foundation for further research. Future studies can explore the application of the system with a wider variety of crops and investigate potential optimizations to further enhance yield and efficiency. As advancements in automation and sensor technology continue, rotary hydroponics has the potential to become a cornerstone of sustainable and secure food production for the future.

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Data availability No datasets were generated or analyzed during the current study. All data supporting the findings of this study are included within the manuscript.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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