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HYDROPONIC SOLUTION FOR SOILLESS AGRICULTURE WITH ADVANCED TECHNIQUES AND SMART PERSPECTIVES

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Abstract: Currently the new method of cultivation called the hydroponic cultivation is gaining reputation all around the international due to green resources control and high-satisfactory meals production. Soil based cultivation methods of primarily based totally agriculture is now going through numerous demanding situations such different herbal disaster, urbanization weather change, improper or more of chemical compounds and insecticides which is depleting the soil nutrition components or fertility. Soil is normally the maximum to be had developing medium for plants. It affords anchorage, nutrients, air, water, etc. for successful plant increase. However, soils along with the above advantages also do pose severe obstacles for plant increase too, at times. In the soil there is a presence of disorder causing organisms, mistaken error soil reaction, unfavourable uses of soil compaction , bad water drainage, degradation due to numerous reasons such as erosion etc. are a number of them. In addition, traditional crop developing in soil (Open Field Agriculture) is somewhat tough because it includes massive space, lot of labour and massive extent of water. Moreover, a ie we consider the metropolitan areas for cultivation, soil isn't to be had for crop developing at all, or in a few areas, we discover shortage of fertile cultivable arable lands due to their unfavourable geographical or topographical conditions . Recently, every other severe trouble skilled due to the fact is the trouble to rent labour for traditional open discipline agriculture. Under such conditions, soil less agriculture can be added successfully. This project discusses a review of smart hydroponic agriculture.

Keywords: **Hydroponic, Soilless, Land, Cultivable etc.**

I. INTRODUCTION

The rapid growth of the global population, particularly in urban regions is expected to be projected to nearly double within the next three decades has significantly intensified the ongoing demand for food which indirectly has immense pressure on available arable land. This rising concern for food security has propelled ongoing research and innovation in sustainable agricultural practices. Among these, vertical farming integrated with advanced technologies has emerged as a viable alternative and complementary solution to traditional agricultural systems, such as greenhouses.

Achieving sustainable food production in the future necessitates addressing the interconnected challenges associated with environmental degradation, societal needs, and resource limitations. Declining number of farmers have resulted today in reduced crop production which indirectly results in reduction in cultivable land contributing to environmental pollution and reduced soil grade. Extreme weather events continues to impact conventional cultivation adversely due to this more frequently.

Considering the above there is a method of soilless cultivation technique which is known for its ability to produce high-quality crops using minimal resources. The hydroponic system technique is being increasingly recognized and also adopted for its efficiency in resource management, improved yield, and ability to operate under controlled environmental conditions. The current soil-based agriculture is susceptible to soil degradation, chemical dependence, and pest infestations in comparison to the hydroponic farming which enables controlled, pesticide-free cultivation even in non-arable regions.

The hydroponic approach makes uses of various inert growing non soil mediums such as gravel, vermiculite, rock wool, peat, sawdust, coir dust, and coconut fibers to support plant development. This also contributes to faster cycles and year-round production with the possibility of minimal disease occurrence, and reduced waste generation. Additionally hydroponic systems conserve water through recirculation mechanisms, which also makes them suitable for deployment in regions facing water scarcity.

If we implement such techniques it would be cost-efficient, and low-maintenance agricultural systems that can operate with reduced manual intervention and optimized operational costs. The advantages of the hydroponic system is it will provide reliable and resource-conscious food production and also stands as a promising solution to meet the future challenges of global food demand, environmental sustainability, and urban agricultural integration.

I.I RELEVANCE

Hydroponics refers to the method of growing plants in nutrient-rich solutions, either without soil or with the aid of inert growing mediums such as gravel, vermiculite, rock wool, peat moss, sawdust, coir dust, or coconut fibre, which provide the necessary mechanical support for plant growth. With the rapid pace of urbanization and industrial development, there has been a notable decline in cultivable land alongside the emergence of several negative environmental impacts caused by traditional farming methods. To make sure there is sustainable food production for the ever-increasing global population, it is imperative to adopt innovative cultivation techniques that address land and water scarcity.

One such approach involves modifying the growing medium to enable sustainable agricultural practices while conserving rapidly depleting land based and water based resources. In this context, soil-less farming techniques have gained considerable attention as promising alternatives for the cultivation of nutritious food crops, vegetables, and ornamental plants. This will consist of the various systems such as hydroponics (soilless or water based agriculture), aquaponics (aqua-agriculture), aeroponics (aero-agriculture), and substrate-based cultivation. If we cosider from these different systems the , hydroponics is considered as a leading solution due to its efficient resource utilization and potential for good grade or yeild food production in controlled environments. A wide range of commercial and specialty crops can be successfully cultivated using hydroponic methods, making it a scalable and sustainable alternative to conventional agriculture.

I.II LITERATURE REVIEW

With respect to proposed work an extensive literature survey is conducted accordingly which is present below.

1. **Nisha Sharma et al.** discussed the emerging potential of hydroponics as a promising cultivation technique in recent years. The ability to grow short-duration crops, particularly vegetables, throughout the year using minimal space and labor makes hydroponics highly suitable for areas with limited access to soil and water. This technique also offers a valuable opportunity for economically disadvantaged and landless individuals to engage in food production. In the Indian context, the hydroponics sector is expected to witness exponential growth in the near future. However, for widespread industrial adoption, there is a pressing need to develop low-cost hydroponic technologies that minimize reliance on manual labor while also reducing overall setup and operational expenses.[1]
2. **Elvira Molin and Michael Martin** evaluated the relevance of vertical farming, particularly in regions with extreme climatic conditions such as Scandinavia. While vertical farming is characterized by relatively high energy consumption compared to conventional agricultural practices, it utilizes other critical resources—such as water, nutrients, arable land, and pesticides—more efficiently. The approach offers the advantage of enabling food production within urban environments, thus supporting local employment and improving food accessibility. However, comprehensive life-cycle assessments comparing vertical farming to traditional agricultural methods are limited, especially in the context of potted herb production. Nevertheless, vertical farming presents substantial benefits in terms of reduced chemical usage and fertilizer application, and can contribute positively to public health and food system resilience by reducing dependence on global supply chains and long-distance transportation, ultimately fostering more self-sufficient and robust local communities[2].
3. **Naga T. Nguyen et al.** emphasized the widespread application of hydroponic systems both in plant biology research and in commercial cultivation of crops like lettuce and tomato. These systems are instrumental in studying plant responses to biotic and abiotic stresses. The researchers presented a detailed protocol for setting up hydroponic systems that can be easily adopted in laboratories focusing on plant mineral nutrition research. The components required for the proposed setup are readily accessible and donot require sourcing from multiple sources making it easy for setup of such system. This required controlled nutrient environments or where the collection of intact root samples is necessary for downstream analysis. Additionally, the nutrient solution concentrations can be modified to examine plant responses to both essential and toxic elements, thus broadening the scope of plant nutrition studies[3].
4. **Paolo Sambo et al.** has caried out research work on the scope and opportunities within the context of smart agriculture, particularly dealing on soilless cultivation systems. These systems offer a viable alternative for agricultural production, especially in regions affected by severe soil degradation and water scarcity. Soilless methods, including hydroponics, align with environmentally sustainable agricultural practices and contribute significantly to the broader goals of global food security. The study examined the mechanisms and processes involved in hydroponic systems that ensure adequate nutrient

availability and efficient uptake by plants, thereby preventing nutritional imbalances that could compromise crop quality. Current research also highlights the ability to manipulate parameters such as nitrate levels and electrical conductivity in nutrient solutions, allowing for precise control over plant health and productivity. Thus, hydroponics presents a tangible, forward-looking strategy that can help overcome many of the limitations currently faced by traditional agriculture[4].

5. **In a continuation of their work**, Paolo Sambo et al. reiterated the significance of soilless systems in overcoming the limitations posed by deteriorated soil conditions and limited water availability. These systems present a practical and eco-friendly response to modern agricultural challenges. The review specifically aimed to explore the functional boundaries and potential of hydroponic techniques within soilless cultivation, placing particular emphasis on mineral nutrient uptake and its implications for crop quality. The research offers detailed insights into the mechanisms that ensure nutrient balance in hydroponic solutions, thereby enabling optimal nutrient acquisition without inducing deficiencies or toxicities. This precise nutrient management is fundamental to maintaining high crop quality and achieving sustainable agricultural practice.
6. **Mahsa Daryadar**, in her research study on *Mentha piperita L.* (peppermint), further stressed that relevance of hydroponic solutions as a key contributor to environmentally conscious agriculture. Her work aligns with the aim of the sustainable food security and proposes to investigate the limitations and prospects of hydroponic systems within soilless cultivation frameworks. Research stressed on understanding the nutrient absorption mechanisms in hydroponic solutions that facilitate efficient nutrient uptake while avoiding nutritional disorders, which can have direct consequences on crop quality. The findings support the ongoing transition towards precision agriculture and environmentally sustainable crop production method[7].

Hydroponic systems are currently being been widely studied as sustainable alternatives to traditional farming, offering efficient water and nutrient usage, especially for vegetable production. Various methodologies such as wick, drip, NFT, and vertical stacking have been explored to enhance yield in limited spaces, particularly in urban areas. While these techniques offer advantages like year-round cultivation and protection from environmental factors, they often require high initial investment and technical knowledge, posing barriers to large-scale adoption. Research has also focused on the role of hydroponics in controlled experiments for studying nutrient dynamics and plant responses, although such setups can be complex and expensive.

Using Smart Tools like multi-parameter sensors and intelligent control algorithms to optimize nutrient delivery in real-time. Despite the progress, issues related to nutrient solution chemistry, system specificity, and crop limitations persist. Studies comparing open and closed hydroponic systems have provided insights into cultivar-specific performance, but applications remain narrow. Overall, while hydroponics holds significant potential for sustainable cultivation, especially in land- and water-scarce regions, efforts must be directed toward simplifying system design and reducing operational costs to enable wider adoption.

II. PROBLEM STATEMENT

There are many challenges in environment such as which include different types such as water scarcity and pollution are becoming increasingly prevalent across the globe, posing a direct threat to sustainable food production. The situation is expected to be more problematic in future in the coming years, which is the need to search for the alternative solutions. Food security is related and dependent on various environmental factors, including the quality and availability of water, soil fertility, and access to energy resources. However, the we have been using agricultural lands over recent decades for prolonged usage has led to a multitude of environmental issues, exacerbating the strain on natural ecosystems.

Climate change has also contributed to degrade both the quality and quantity of water resources, which are already under degradation process. Simultaneously, with the widespread use of pesticides in conventional agriculture has accelerated soil degradation and erosion an issue that not only dampers or hinders agricultural productivity but also contributes to air and water pollution. Soil-borne pests continue to disrupt crop growth, and while pesticides are commonly used to counteract them, their runoff into nearby water bodies contaminates aquatic ecosystems and threatens biodiversity.

With the study of these challenges is it necessary to explore the alternatives that minimize environmental damage, particularly pollution and soil erosion. The transition from traditional soil-based farming methods to more advanced, environmentally conscious practices is essential. In this regard, the integration of modern technologies, particularly artificial intelligence-driven smart agricultural systems, holds significant potential. These innovations can offer precision control, resource optimization, and environmentally friendly practices, paving the way for resilient and sustainable agricultural systems in the face of growing environmental threats.

III. HYDROPONICS AND IOT

In hydroponic systems, plants are cultivated without the use of soil, relying instead on nutrient-rich, aerated water to deliver essential minerals and oxygen directly to the root zone. This technique enables cultivation in urban areas by allowing homesteads to operate soilless systems in compact environments. The integration of Internet of Things (IoT) technologies further enhances this method, offering the ability to intelligently monitor and autonomously manage the hydroponic environment through interconnected sensors and cloud-based platforms. The primary objective is to develop a system capable of making autonomous decisions for regulating the hydroponic environment based on real-time sensor inputs.

Hydroponics requires precise control of various parameters, including nutrient composition, water aeration, and temperature regulation, to avoid root stress and minimize the risk of pathogen proliferation. These systems, while efficient, often involve intricate mechanical and electronic components that may appear complex to small-scale growers or hobbyists. Therefore, nutrient delivery in hydroponics must be tailored in accordance with Liebig's Law of the Minimum, ensuring that each plant receives the optimal balance of elements necessary for growth.

The IoT framework involves a network of connected devices that can collect data from sensor nodes and transmit it to a cloud-based infrastructure for analysis, visualization, and control. By continuously logging environmental data from the hydroponic setup, the system can identify trends, diagnose issues, and enable remote visualization through mobile or web-based interfaces. Moreover, the integration of IoT allows for remote regulation and automation of the hydroponic conditions, significantly improving system efficiency, reducing manual intervention, and fostering sustainable crop production in controlled environments.

IV. PROPOSED METHODOLOGY

The proposed system is developed in a systematic sequence of phases to ensure reliability, and accuracy throughout the implementation. Each phase has a specific objective, contributing to the overall automation and intelligent control of the hydroponic system using Internet of Things (IoT) technologies.

1. Literature Review and Component Selection:

A comprehensive literature review was conducted to understand the current limitations in hydroponic farming and existing automation approaches. Based on this, suitable components and sensor nodes were shortlisted to fulfill the monitoring and automation objectives of the system.

2. Development of IoT Communication Protocols:

In this phase, communication protocols were developed to facilitate real-time data transfer from the hydroponic hardware system to the cloud-based software application. The data can be visualized by users through a web portal or a mobile app, enabling remote monitoring and control.

3. Temperature and Humidity Measurement :

A temperature and humidity sensing module (DHT11) was integrated to continuously monitor environmental conditions. Based on the sensed values, if the temperature exceeds a pre-defined threshold, a cooling system is automatically activated to stabilize the internal climate of the hydroponic unit.

4. Development of pH Monitoring Subsystem:

Ph monitoring and control plays a very important role in the hydroponic systems. A pH sensor will be interfaces to monitor the acidity or alkalinity of the nutrient solution. Based on the sensor readings, corrective actions can be taken either manually or through automated approach as per the selection.

5. Sensor Node Integration and Cloud Connectivity:

All environmental data including light intensity, temperature, humidity, and pH are read from their respective sensors and transmitted via the ESP8266 microcontroller module to a cloud server. This setup enables remote access to real-time parameters making it easier for realtime monitoring and control decision making.

6. Automation Algorithm for Control of Hydroponic Parameters:

Control algorithms for the automation post sensor data collection will be developed and deployed on the microcontroller unit to automate responses based on sensor data. This includes control commands for the automation of lighting, temperature, and nutrient flow based on real-time environmental changes to maintain the optimum environment fot eh same

7. Hardware Design and PCB Development:

The electronic components are to be assembled on a custom-designed PCB. The hardware includes relays, sensor interfaces, LCD display, and microcontroller modules for data acquisition and actuation. Schematic design and PCB layout were created using EasyEDA, followed by fabrication and testing.

8. Software and Application Development:

A user-friendly web and mobile interface will be developed to visualize the sensor data and enable manual override if needed. This system is capable of logging historical data and can trigger alerts based on critical sensor thresholds.

The proposed architecture Diagram of the system is given below:

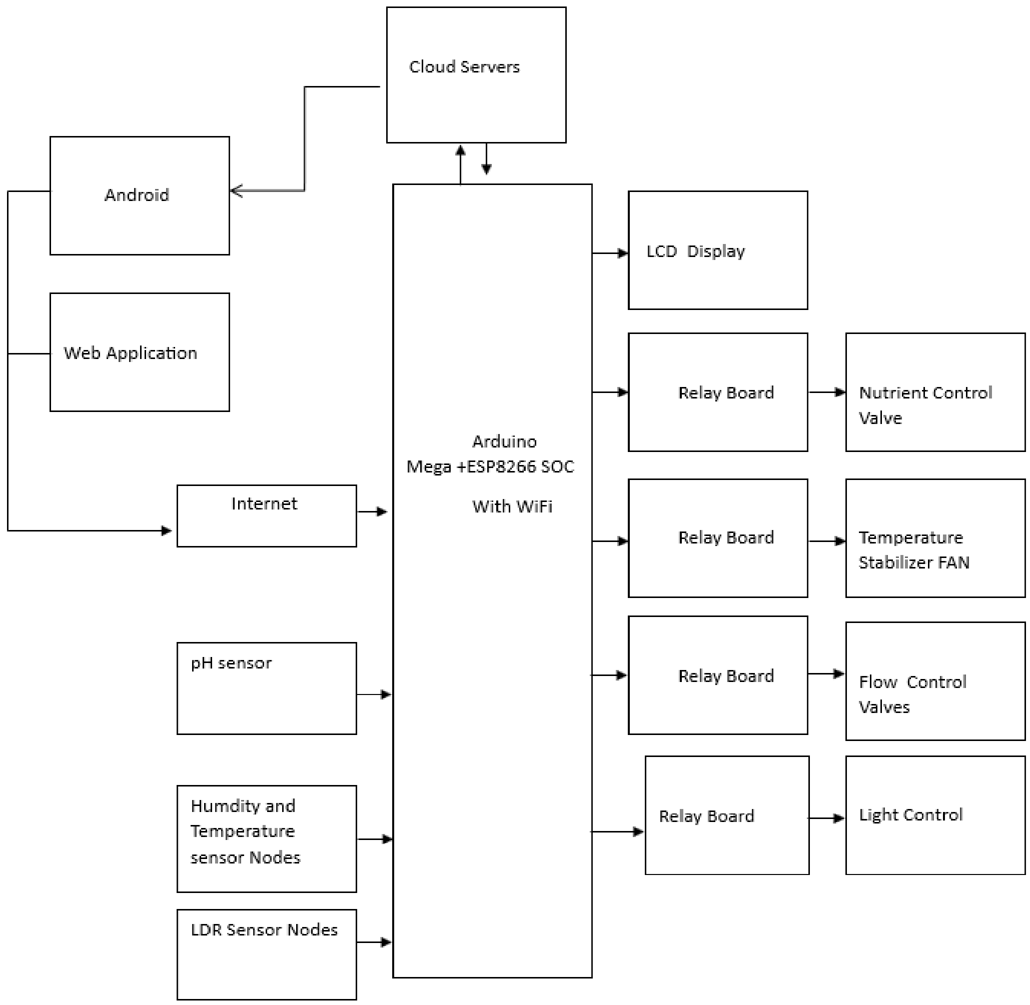

Figure 1: Proposed System Architecture

The figure below illustrates the block diagram of the working principle of the proposed system. As shown in the above diagram, the system comprises multiple sensor nodes interfaced to the primary microcontroller unit turning it into a smart hydroponics automation, monitoring, and control framework. The developed prototype is divided into two primary modules: the intelligent hydroponic unit and the IoT-enabled portal designed for real-time remote monitoring and visualization of sensor data. The smart system can continuously keep a track of key environmental parameters such as pH, light intensity, temperature, and humidity. Based on the sensor readings, the nutrient film control valve is actuated to maintain optimal growth conditions. The sensor nodes are interfaced with a central microcontroller which executes automation logic to regulate environmental parameters accordingly. Additionally, the data which is monitored is transmitted to the cloud, allowing remote access through the web or mobile application for informed decision-making and enhanced system transparency.

V. CONCLUSION

Hydroponic cultivation techniques discussed in this paper for automated approach offers a reliable and powerful alternative to soil agriculture by eliminating exposure to soil-borne pests and diseases, This not only reduces the dependability on soil preparation, insecticides, and fungicides but also reduces the stress on the farmers. This not only lowers operational costs but also enhances crop hygiene. Additionally if we consider the delivery of nutrient-enriched water to plant roots, this minimizes water loss through runoff or evaporation, ensuring efficient resource utilization.

Throught the recent years hydroponic farming has evolved into a well-established and widely accepted practice. From the study conducted it is evident from various countries it is justified for is viability and numerous advantages over conventional farming methods, such as improved resource efficiency, reduced spatial requirements, and increased productivity. This has spurred considerable technological advancement and adoption globally.

The implementation of Internet of Things (IoT) technology into hydroponic systems such as rooftop farms, vertical farming units, and smart green building has facilitated and boosted their strategic placement in or around urban centers. This proximity significantly reduces transportation costs and post-harvest losses, while also enabling real-time monitoring and safe transit via IoT-enabled logistics stations. Centralized web platforms can be developed to visualize sensor data through dynamic graphs and dashboards, thereby assisting farmers and researchers in informed decision-making.

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