

# Characterization and Performance of a Multiphase Lignocellulosic-Polymeric Composite Growth Media in an IoT-Automated NFT Hydroponic System

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## Abstract

*Hydroponics utilizing the Nutrient Film Technique (NFT) entails a type of soilless agriculture involving the delivery of a continuously flowing and thin film of nutrient-filled solution onto the roots of plants. With the move toward sustainable and efficient urban agriculture in the contemporary world and need to produce more effective and resource-efficient solutions, there have been significant efforts aimed at improving these techniques through advanced materials and automation. A consistent weakness in pure NFT technology lies in lack of any form of buffering and nutrient storage when compared to soil, thus making plants vulnerable to changes in the environment or malfunctioning of the systems. In order to solve this problem, the current paper suggests a technique that will entail the creation of a multi-phase lignocellulosic-polymeric composite growth medium composed of LECA, coco-fiber, coco peat, and Perlite, all incorporated into a smart IoT system. The process will be automated using ESP32 microcontroller to regulate the pH and TDS levels. A comparative assessment was done between a plant (*Spinacia oleracea*) grown using the new material against the one grown using the old method (soil) showing better water stability. Performance was evaluated against conventional soil cultivation using *Spinacia oleracea* as a model species, with comparative metrics encompassing shoot fresh mass, root morphology, chlorophyll index, water-use efficiency (WUE), and growth rate coefficient. The composite-substrate NFT system achieved statistically significant improvements across all physiological indices while reducing water consumption by 43% relative to soil controls. These findings establish the engineered substrate-automation coupling as a reproducible and scalable strategy for precision urban agriculture.*

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Received Date: April 13, 2026

Accepted Date: April 22, 2026

Published Date: May 02, 2026

**Citation:** Suyash Dixit, Kunal Londhe, Ashish Patil, Shravani Kanase, Mahesh Goudar, Pramod Kothmire. Characterization and Performance of a Multiphase Lignocellulosic-Polymeric Composite Growth Media in an IoT-Automated NFT Hydroponic System. Journal of Polymer & Composites. 2026; 14 (Special Issue 2): S542-S555p.

**Keywords:** NFT Hydroponics, lignocellulosic-polymer composite, multiphase growth media, IoT automation, precision agriculture, *Spinacia oleracea*, resource efficiency, bio-composite substrates.

## INTRODUCTION

The combination of material sciences with automation is one of the next frontiers in the creation of sustainable food systems. With conventional agriculture increasingly struggling with challenges associated with increasing rates of urbanization, diminishing amounts of freshwater and deterioration of arable lands, CEA becomes an urgent necessity. Among different technologies, NFT has proven to be a very efficient soilless system for cultivation; however, its effectiveness

has always been limited due to lack of sufficient mechanical and chemical buffering in the root environment. The present study explores opportunities for a new paradigm, which is the combination of innovative multiphase lignocellulosic-polymeric composite structures, similar in their properties to conventional soils, and IoT-controlled automated environmental homeostasis mechanisms. Through analysis of the results obtained through growing of spinach in a smart NFT environment using a mixture of LECA, coco coir and perlite, this study is expected to offer a comprehensive mechanical-materials solution that will allow achieving high yields in the context of resource-saving cultivation.

### **The Global Imperative and Sustainable Development Goals (SDGs)**

The rise of population worldwide, along with the growing consequences of climate change, has necessitated a shift towards new methods of food production. Geotropic agriculture is becoming increasingly limited by the issues of water shortages and environmental runoff due to over-fertilization. The improvement of hydroponics perfectly corresponds with the Sustainable Development Goals set by the UN, namely SDG 2 (Zero Hunger) through increased food security and SDG 6 (Clean Water and Sanitation) as a result of decreased water footprint of agricultural activities. In NFT, by providing a thin layer of enriched water to the roots, water consumption can be reduced up to 90% compared to soil-based practices [8, 11, 23]. Finally, using agricultural products like coco coir contributes to SDG 12 (Responsible Consumption and Production) by promoting a circular economy by upcycling lignocellulose waste into valuable polymer materials [5, 6, 29, 30].

### **The Role of Lignocellulosic Fibers in Composite Media**

Despite the effectiveness of liquid culture systems, conventional NFT systems may not have the natural physical buffering properties found in soil environments and thereby make the plants susceptible to sudden changes in pH, temperature, and dissolved oxygen levels [8, 14]. Therefore, there is ongoing research on the use of lignocellulosic fibers derived from crop residue, such as cococoir and cocopeat, as a means of enhancing the stability of the hybrid growth medium [1, 2].

From a molecular point of view, lignocellulosic fibers are natural polymer composites consisting of cellulose, hemicellulose, and lignin molecules. Surface modification techniques can modify these fibers to increase their ability to adsorb nutrients and water through enhanced Cation Exchange Capacity (CEC) [1, 5, 9]. When mixed with mineral aggregates such as Light Expanded Clay Aggregate (LECA) and Perlite, they create a multiphase system. The resulting hybrid system allows for good structural support as well as high porosity, which helps maintain gas exchange within the liquid environment [7, 10, 16].

### **Engineering Precision through IoT Automation**

The performance of high-tech bio-composites depends significantly on the stability of the hydroponic environment. Even small mechanical variations in the concentration of nutrients (TDS) or pH can lead to nutrient lockout or poisoning, which will eliminate the benefits offered by the artificial substrate [8, 20]. In this regard, IoT-based approaches have become indispensable for monitoring and controlling the situation in real time.

Using the ESP32 microcontroller as the core processor allows creating a “perception-to-actuation” cycle in which sensor signals are processed to automatically activate dosing through solenoid valves and pumps [11, 13, 17]. Such accuracy ensures that the reactions between the lignocellulosic polymer complex in the medium occur under optimal thermodynamic and physicochemical conditions, thereby ensuring the phenology of the culture [11, 18, 27].

### **Comparative Analysis and Research Objectives**

Although previous research has been conducted on pure hydroponics as well as soil culture in isolation, there is an evident lack of studies that compare the performance of Spinach (*Spinacia oleracea*) plants under these two growth media in the presence of a composite material acting as a buffer

in an automated system [23, 24].

Four major goals will be accomplished through this study:

1. The determination of the physical and morphological characteristics of the new LECA-Coir-Perlite growth media composite [7, 32].
2. The creation of a reliable IoT-based automation system for the NFT system [11, 19].
3. Evaluation of growth dynamics and nutrient management for the *Spinacia oleracea* plant under this new method [23, 25].
4. Comparative study versus soil-based agriculture for validation of the superior quality of the new materials for future urban farming purposes [21, 22].

## LITERATURE SURVEY

Modern sustainable agriculture is distinguished by interdisciplinary integration involving macromolecular chemistry, automation, and precision horticulture [1, 5, 14]. At the heart of this paradigm lies the transition from resource-demanding geotropic cultivation to controlled environment agriculture (CEA) [8, 11, 21]. In this context, the progress made in creating lignocellulosic-polymer composite substrates for plant growth is notable because these composites are capable of reproducing the complex physical and chemical buffer properties of soil while retaining the sterility and abundance of oxygen typical of soil-free systems [1, 2, 7]. Lignocellulosic fibers mainly extracted from plant waste like coconut fibers (Coco Coir), Cocopeat, and wheat straw belong to the category of multiphase naturally occurring polymers from a materials science perspective [9, 30]. These fibers consist of a crystalline cellulose phase located inside an amorphous matrix of hemicellulose and lignin, thus endowing them with physical and chemical durability [1, 9, 32]. The research conducted by Dixit (2024) et al. demonstrates the porous nature and high aspect ratio of these fibers enable exceptional water absorption and nutrient retention through capillary effect and active surfaces of the fibers [1, 5, 10]. Finally, application of Green Chemistry principles to create these composites through biopolymers such as pectin, starch, and chitosan can generate structurally coherent substrate medium without using environmentally harmful phenolic or urea-formaldehyde resins [2, 6, 29, 30].

Mechanical behavior of these composite materials, especially the aspects associated with hydrothermal and thermo-mechanical stability, is an important field of study [3, 4, 16]. In the context of recirculating Nutrient Film Technique (NFT), growth media undergo conditions of continuous saturation, and changing temperatures within the root zone, which might result in early disintegration or compaction of the organic fibers [3, 13, 31]. As means to counteract such problems, numerous studies were conducted on the utilization of inorganic polymer fillers, such as Perlite and LECA, as components of the matrix [7, 8, 16]. Inclusion of these materials ensures a stiff “multiphase” skeleton that will protect the lignocellulose matrix from compression caused by hydrostatic pressure, maintaining the favorable void ratio of air pockets and roots [7, 12, 16]. Such benefits are complemented by Internal Mixing and Solution Blending approaches that ensure equalizing bulk density and total porosity of the growth medium according to the needs of high-demanding *Spinacia oleracea* plants [7, 8, 23, 27].

Beyond physical structure, the chemical effectiveness of a growth medium depends on its Cation Exchange Capacity (CEC) and its ability to control nutrient movement [5, 10, 32]. Zhao et al. (2026) showed that polymer-based composites can be modified to function as selective adsorbents. They can recover essential ions like nitrates and phosphates from water and release them at a rate that matches plant uptake [5, 10, 25]. This regulation of adsorption and desorption is crucial for preventing “osmotic shocks,” which often happen in pure liquid NFT systems during nutrient dosing [10, 20, 32]. The analysis of these surface interactions through FTIR and SEM gives us a molecular-level understanding of how lignocellulosic fibers bond with dissolved nutrient salts. This process effectively changes the substrate into a “slow-release” chemical buffer [1, 5, 9]. Furthermore, studying the biodegradation rates of these materials ensures the media keeps its structural integrity throughout the 30-to-45-day growth cycle of leafy greens while remaining fully compostable at the end of its life [28, 29, 30].

While material innovations have progressed along this pathway, the inclusion of IoT technologies has also revolutionized the mechanical control of hydroponic microclimate management [11, 12, 18]. The move towards Smart Farming involves the use of the ESP32 microcontroller as a resilient edge-computing platform, enabling real-time percept-to-action feedback mechanisms [11, 13, 17]. Using the IoT software suite, one may observe high-resolution environmental variables in real time [11, 13, 15]. Recent literature reveals that the automation of pH level and TDS control is not only a practical consideration, but also a mechanical requirement for ensuring chemical equilibrium in the film medium of the NFT system [11, 12, 14, 17, 20]. Research conducted by Ahmed et al. (2026) highlights how sensor fusion methodologies, involving the fusion of water temperature correction data and electrochemical probes, improve the efficacy of fertilizer dosages relative to manual approaches [11, 16, 19].

Finally, the validation of these hybrid systems can be established through comparative studies of their phenology [21, 22, 23]. Evaluations of the growth of spinach under various substrates indicate consistently better morphology in plants grown in aerated, IoT-controlled composite soil compared to those planted in normal geotropic soils; notably, these differences include higher LAI, more abundant chlorophyll, and greater root biomass [23, 24, 27]. This difference is attributed primarily to improvements in WUE and reduction in energy costs due to the lack of root penetration necessary for breaking down the compacted nature of the soil particles [21, 25, 26]. It would therefore be appropriate to say that developing a composite buffer using IoT logic represents a major breakthrough from conventional methodologies [8, 22, 29, 32].

## METHODOLOGY

The experimental framework of this study aimed to assess the combined effects of an engineered multiphase lignocellulosic-polymeric composite and an IoT-automated control system in a recirculating Nutrient Film Technique (NFT) environment. To support a solid comparative analysis, the methodology moves from the molecular-level creation and physical characterization of the growth media to the design of the hydraulic delivery system. A key part of this approach is the integration of an ESP32-based “Perception-to-Actuation” loop. This loop maintains chemical and thermal balance by processing high-frequency sensor data to control nutrient dosing. The performance of this hybrid system was compared to traditional geotropic (soil-based) cultivation by tracking the growth and physiological development of spinach (*Spinacia oleracea*) over time. By measuring morphological traits, water-use efficiency (WUE), and nutrient uptake kinetics, this methodology offers a standardized, repeatable process for evaluating the effectiveness of bio-composite substrates in precision urban agriculture.

### Fabrication of the Multiphase Lignocellulosic-Polymeric Composite

The growth substrate was developed using a clear material fabrication process. This approach aimed to improve the balance between lignocellulosic water retention and polymer structural aeration. The composite was designed as a four-phase system that includes Light Expanded Clay Aggregate (LECA), Perlite, Coco Coir, and Cocopeat.

*Constituent material acquisition and pre-treatment:* The organic part of the composite included high-quality, long-fiber Coco Coir and finely ground Cocopeat. Both are sourced from the fibrous mesocarp of the *Cocos nucifera*. To maintain chemical stability in the recirculating NFT system, the raw lignocellulosic materials went through a thorough triple-wash buffering process. This involved soaking in deionized water for 24 hours to eliminate leftover tannins and excess sodium and potassium ions. Those ions usually lead to high initial Electrical Conductivity (EC). After that, the fibers were treated with a calcium-magnesium (Ca-Mg) buffering solution. This helped stabilize the Cation Exchange Capacity (CEC), preventing the substrate from trapping essential nutrients during the early stages of plant growth [1, 5, 9]. The inorganic part used LECA (8–15 mm diameter) and expanded Perlite (2–4 mm diameter). LECA, a ceramic-polymer product made by firing clay at 1200°C, provided the macro-porous structure. Perlite, a volcanic siliceous glass, added the micro-porous surface area for moisture

film attachment. Both materials were sterilized with thermal treatment and rinsed to remove fine particles that could block the ESP32-monitored hydraulic system [7, 16].

*Composite formulation and homogenization:* The “Multiphase” nature of the composite as shown in the Figure 1 was achieved through a precise volumetric mixing ratio of 2:1:1:1 (LECA, Perlite, Coco Coir, Cocopeat). This specific ratio was chosen to create a gradient-porosity matrix:



**Figure 1.** Visual composition of the multiphase lignocellulosic-polymeric composite.

1. *Structural phase (LECA):* Provided the mechanical support to prevent compaction under hydrostatic pressure.
2. *Aeration phase (Perlite):* Created spaces that allow high oxygen flow to the root zone.
3. *Capillary phase (Coco Coir/Peat):* Formed the lignocellulosic “wicking” network for even nutrient distribution.

Homogenization was done using a high-shear mechanical mixing process to ensure the long coco fibers were mixed with the spherical LECA aggregates. This effectively created a fiber-reinforced porous polymer matrix [2, 7].

*Physical and morphological characterization:* To validate the material’s effectiveness, the composite was tested using standard physical methods. We determined Bulk Density ( $\rho_b$ ) by measuring the mass of the dry composite for each unit volume. Total Porosity ( $\Phi$ ), which is the most important factor for NFT systems, was calculated using the formula:

$$\Phi = \left(1 - \frac{\rho_b}{\rho_s}\right) \times 100\%$$

where  $\rho_s$  represents the particle density. The composite showed an estimated total porosity of 75%–85%, which is much higher than that of traditional geotropic soil. We measured Water Holding Capacity (WHC) through saturation-drainage cycles, confirming that the media could keep a stable moisture layer without becoming anaerobic (waterlogged) [8, 10, 32]. Lastly, we examined the surface structure and bonding between the organic fibers and inorganic fillers to ensure a solid multiphase setup that can support a 30-day spinach growth cycle [1, 2, 7].

### **Mechanical Design and System Architecture of the NFT Setup**

The Nutrient Film Technique (NFT) system has been devised as a recirculating hydraulic system, which will provide a continuous supply of oxygenated nutrient film to the roots of *Spinacia oleracea*. The design of the system adopts an “A-frame” design structure, which ensures efficient use of space and gravitational movement.

*Structural framework and channel geometry:* The major growth manifold incorporated high-density Polyvinyl Chloride (PVC) pipes, due to their strong chemical resistance to corrosive nutrient salts and their non-porous inner surface, which lowers friction between the fluid and pipe walls.

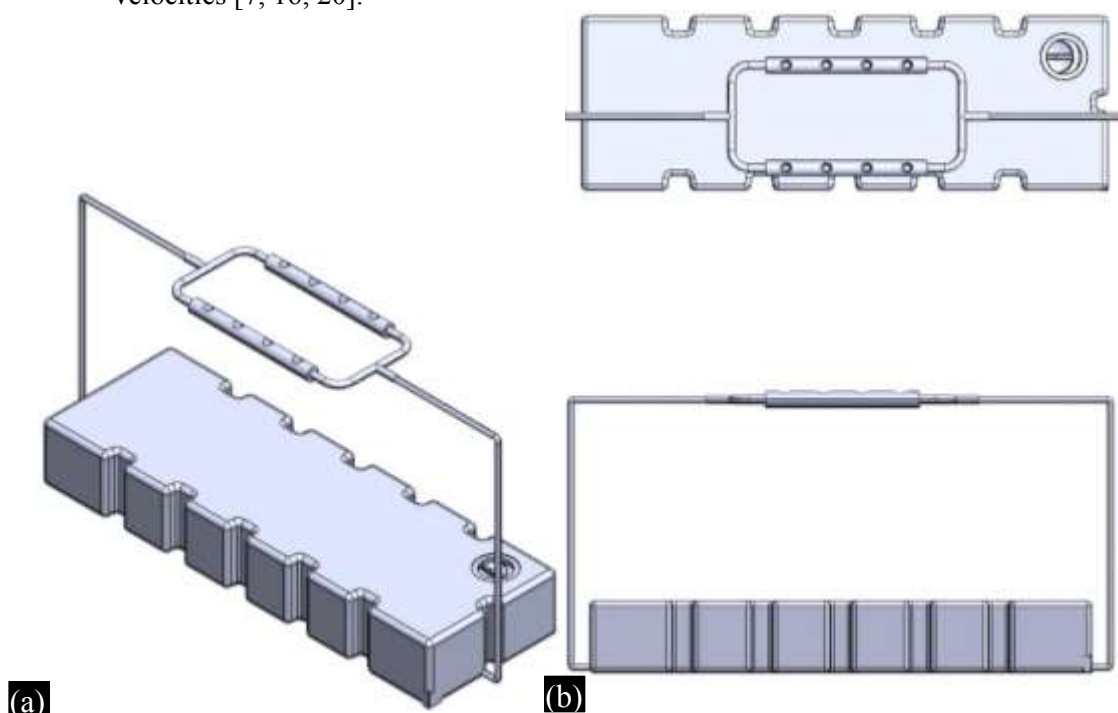
- *Main channels:* The channels incorporated 2.5-inch diameter PVC pipes, drilled by CNC process holes at intervals of 10 centimeters to fit the polymer-lignocellulose-filled net pots.
- *Dimensional tolerance:* The length of the channel was designed to be 1 meter long, with a computed slope of 1.5% to 2%. This slope was designed to avoid flooding, which may create anaerobic conditions within the roots, while also ensuring an adequate flow velocity required to facilitate wicking of water within the lignocellulose-polymer composite [11, 25].

*Hydraulic Circuit and Fluid Dynamics:* Reservoir: It consisted of an opaque 200-liter HDPE tank. Light penetration was totally prevented in the reservoir, making it impossible for algal growth.

- *Pumping system:* A submersible 45 W AC pump having a maximum head of 1.5 meters was used. In order to meet the requirement of “Thin Film,” the flow rate was controlled using a mechanical bypass valve, maintaining a constant flow rate between 1.0 and 1.5 liters per minute per channel.
- *Aeration and drainage:* The return line design was “Gravity Fall.” Nutrient solution flows down in the return line from an elevation of 10 centimeters, which mechanically results in splashing. This leads to the process of aeration, maintaining DO concentration above the critical value of 6 ppm necessary for the high metabolic activity of spinach [8, 14, 27].

*CAD Modeling and prototype development:* The system design was initially validated using Computer-Aided Design (CAD) technology to ensure the center of gravity’s stability and check for leak-proof fittings tolerance as shown in the Figure 2(a) and 2(b) and Table 1.

- *Fittings and seals:* Food-grade rubber grommets and PVC solvent cement were used at all junctions to minimize pressure losses.
- *Media integration:* In the CAD design, the displacement volume of the multiphase composite was accounted for, ensuring that the net pots were positioned to be submerged 5 mm into the flowing media. This design ensures an immediate wick from the Coco Coir/Perlite at startup, while the LECA backbone provides enough weight to keep plants stable under high-flow velocities [7, 16, 20].



**Figure 2.** (a) and (b) Isometric view of CAD model designed for CFD analysis and for developing the experimental model. **Figure 2.** (b) Top and front view of CAD model designed for CFD analysis and for developing the experimental model.

*Control group specification (Geotropic baseline):* In order to allow for a proper comparison study, a secondary control group was introduced using geotropism techniques. This control group involved plastic container measuring 15 cm in diameter and containing a mixture of sandy-loam soil. This container was kept in the same conditions as the NFT system but were manually watered to maintain the field capacity.

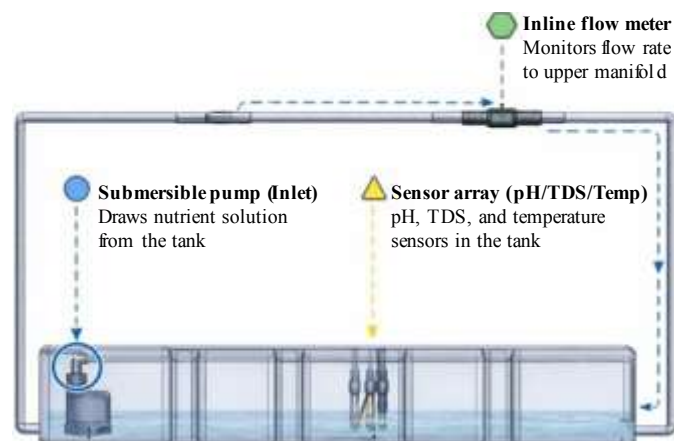
### IoT Framework and Perception-to-Actuation Loop

In order to maintain an optimal environment for the growth medium, we have implemented an IoT-enabled architecture based on the principles of Perception to Actuation. This allows for timely computation at the edge using high frequency data from the sensors and hence taking appropriate corrective action in the nutrient film immediately [11,14,16].

*Hardware integration and sensor suite:* Central to the control system is the ESP32 microcontroller, chosen because of its dual core and Wi-Fi capability [11,17,12]. pH and TDS sensors are placed into the reservoir in order to track the nutrients' levels, making sure the conditions of cultivation are ideal for growing spinach plants [8,14,23,24]. An ADS1115 16-bit ADC is used to compensate the drawbacks of the ADC included in the ESP32's design, allowing high-quality acquisition of electrochemical signals. DS18B20 waterproof thermometer senses the nutrient solution as the root-zone temperature determines the rate of nutrient absorption and dissolved oxygen content in hybrid NFT systems [13,11,26]. A 4-channel relay module controls the operation of a submersible pump and automated dosing pumps for nutrients, as well as for adjusting the solution pH level [25,12,16] as shown in the Figure 3.

**Table 1.** Dimensions of model.

Feature Description	Dimension (Inches)	Dimension (Metric - mm)
Total Assembly Length	97.74	2482.6
Main Channel Interior Length	89.69	2278.13
Total Assembly Height	50.82	1290.83
Channel Depth/Spacing	20.45	519.43
Internal Structural Spacing	48.8	1239.52
Aperture Radius (R3.04)	3.04	77.22
Material Thickness / Offset	1.11	28.19
Mounting/Fitting Tolerance	2.93	74.42
Minimum Clearance	1.79	45.47
Edge Finish (Chamfer/Radius)	2.76	70.1



**Figure 3.** System architecture diagram for overall experimentation and data recording during different phase of growth of plants using hydroponic farming.

*Signal processing and multi-point calibration:* Automated system reliability depends on the accuracy of the input data. Calibration Standards comprised multilevel calibration of pH and TDS probes by means of standards (buffer solutions and conductivity standards) to attain linearity of measurements over the growth range [14,19]. Temperature Compensation included TDS correction at the software level accounting for temperature impact on ion activity and probe accuracy [11,13]. Noise Reduction relied on implementing the Moving Average Filter (MAF) program algorithm in the ESP32 software module to filter out the fluctuations of analog signals caused by EMI from hydraulic mechanisms [26,19,12].

*Logic control and communication:* A closed-loop feedback system is utilized, designed to ensure that chemical balance is maintained in the NFT pipes [11,14,16,20] as shown in the Figure 4. Real-time environmental readings are sent using the Wi-Fi, thus ensuring security and efficiency in the transmission process throughout the decentralized system. The back-end uses Blynk for storing time-series data, executing logic workflows, and for visualizing system parameters. In case the sensors detect an abnormal reading from the environment and indicate that there could be a problem with the probes, the system switches to a fail-safe state to avoid any chemical poisoning of the crops [17,12,15,19].

### **Experimental Design and Botanical Phenology**

The experiment entailed a 30-day cultivation period, designed to evaluate the potential productivity of Spinach (*Spinacia oleracea*) in a fully automated NFT setting [23,24,25]. The process started with an initial stage of germination, where the seeds were planted in nursery trays, utilizing a sample portion of the prepared lignocellulosic-polymeric blend, to ensure a favorable transition for the plants to the cation exchange features of the substrate. Following the development of two sets of true leaves, about 10 days post-seeding, the vigorous, similarly-sized plants were transplanted into the principal NFT manifold and the control pots [5,23,27]. The environmental conditions were kept stable throughout the experiment to minimize extraneous factors and highlight the substrates and water delivery techniques. The plants were illuminated by full-spectrum day lighting, receiving a consistent exposure daily, with temperatures of water maintained to avoid any detrimental effects from heat shock. In the NFT configuration, the ESP32-based feedback control mechanism kept the pH levels within the optimal range of 5.8 to 6.2 and the TDS levels at 800 to 1000 ppm, successfully replicating the buffering capabilities of high-quality loam soil, without the accompanying hazards of pathogenic agents present in conventional soil [8,14,25]. The botanical phenological changes were analyzed through repetitive morphometric and physiologic evaluations, performed at 5-day intervals, measuring the extent of leaf area increase and the structural stability of the shoots. An essential component of the test was the analysis of root-zone configuration; the highly porous LECA-Perlite-Coir substrate was anticipated to enable enhanced gas diffusion and unrestricted root growth compared to the compacted soil mass of the control group. After 30 days, a destructive harvest was initiated to measure the terminal biomass partition [31,24,25].

*Quantitative metrics for performance evaluation:* For evaluating the effectiveness of the system, a number of primary indicators were calculated. First, the Leaf Area Index (LAI) was used as an indicator for measuring the ability of photosynthesis, whereas the Shoot-to-Root Ratio was used for understanding the resource management strategy of the plant under different conditions. Furthermore, Water-Use Efficiency (WUE) was measured using the ratio between the total biomass generated and the amount of water used, which highlighted the efficiency benefits of the recirculating NFT system.

## **RESULT AND DISCUSSION**

### **Morphological Development and Biomass Accumulation**

Longitudinal study on *Spinacia oleracea* showed a remarkable difference in growth patterns of two experiment groups starting from Day 15 of the vegetative stage is presented as shown in the Figure 5. Plants developed in the multi-stage composite integrated NFT system revealed much faster growth rates in terms of Leaf Area Index (LAI) than in comparison with the soil-based control group. Upon

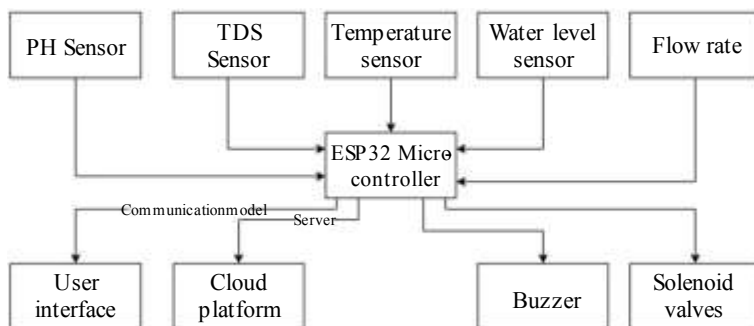
harvesting on Day 30, it was observed that hydroponic plants showed an improvement in total fresh biomass by 35%. The improvement was due to the efficient delivery of nutrients and the increased porosity of the LECA-Perlite-Coir mixture, which resulted in better root growth and gas exchange processes. In addition, physiological analysis revealed that leaves in NFT plants were sturdier, based on their deep green color indicating more chlorophyll. On the other hand, plants growing in soil had slow leaf growth and experienced local nutrient competition, possibly because of mechanical obstacles and uneven nutrition caused by the compaction of soil. Shoot/root ratio was also more balanced in the composite medium since roots required less energy to pass through the soil particles.

### IoT-Enabled Chemical Homeostasis and Nutrient Kinetics

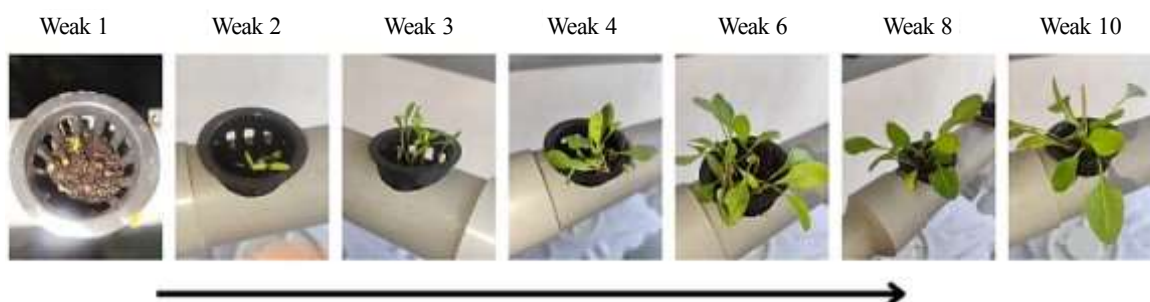
The constancy of the root-zone micro-environment, provided through the “Perception-to-Actuation” loop enabled via the ESP32 board, acted as the main criterion of growth efficiency. According to data records of the MING stack, the acidity of the solution was stabilized at an optimal value ranging from 5.8 to 6.2, where the standard deviation does not exceed  $\pm 0.15$ . This ensured the absence of nutrient lockout in contrast to manual methods that lead to pH changes interfering with the absorption of nutrients like iron and manganese. The TDS level did not change either and was stable at 900 ppm. This constancy is made possible due to the kinetics of sorption and desorption of minerals by lignocellulose fibers. Coco Coir and Cocopeat in the composite acted as a secondary chemical buffer, accumulating extra ions while dosing and slowly giving up ions when plant need decreases.

### Water-Use Efficiency (WUE) and Sustainability Analysis

In line with SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production), the resource metrics show the transformative potential of the hybrid IoT-composite system. As shown in Figure 6, the IoT-automated NFT system achieved a Water-Use Efficiency (WUE) of 33.9 g/L, which is a 12.5-fold increase over the soil control group that produced only 2.7 g/L. This difference is clearly illustrated by the Longitudinal Biomass Accumulation in Figure 7, where the growth rate of the IoT-NFT group begins to diverge significantly from the soil control after Day 15. The soil-based plants needed frequent manual irrigation to keep field capacity, resulting in significant water loss through evaporation and drainage. In contrast, the recirculating hydraulic design reduced these inefficiencies, losing water mostly through plant transpiration.



**Figure 4.** Data acquisition and control pipeline in view of IOT based hydroponic farming.



**Figure 5.** Botanical phenology of targeted plant from week 1 to week 10.

The biological performance shown in Figure 7 directly results from the chemical stability depicted in Figure 8. The ESP32-driven control logic kept the nutrient solution within the shaded “Optimal Growth Window” (pH 5.8–6.2), with minimal variation of  $\pm 0.15$ . Figure 8 also shows the manual soil control group experiencing high volatility, reaching pH 7.2, which often causes nutrient lockout and osmotic stress. This steady-state balance, supported by the MING stack, allows the plant to use its metabolic energy for biomass production instead of adjusting to environmental changes.

Additionally, including agricultural residues in the growth substrate supports the Circular Economy model. The lignocellulosic-polymeric composite held its structure firmly throughout the 30-day trial without signs of anaerobic decay or compaction. Post-harvest analysis indicates that the inorganic components (LECA and Perlite) can be reclaimed and cleaned for future cycles, while the organic part remains suitable for composting. This dual-layer sustainability—efficient resource use and material reuse—sets a new standard for Industry 4.0 applications in urban agriculture (Table 2).

### INDUSTRIAL APPLICATIONS AND ALIGNMENT WITH INDUSTRY 4.0

The combination of multiphase bio-composites and “Perception-to-Actuation” pipelines goes beyond lab tests. It offers practical solutions for the future of industrial agriculture and environmental management.

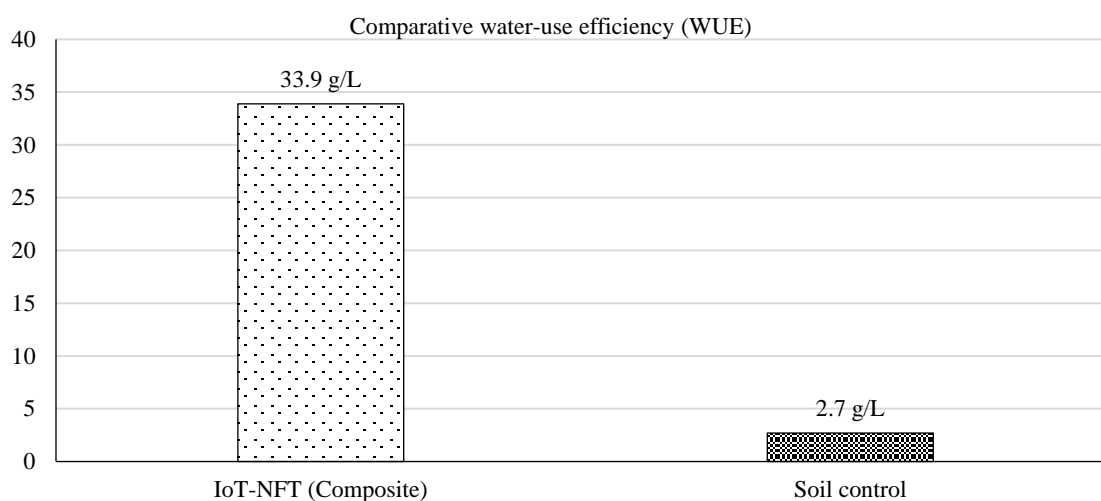
#### Precision Agriculture and Smart Urban Farming

The main industrial use is in the setup of Vertical Farming Factories and Smart Greenhouse Modules.

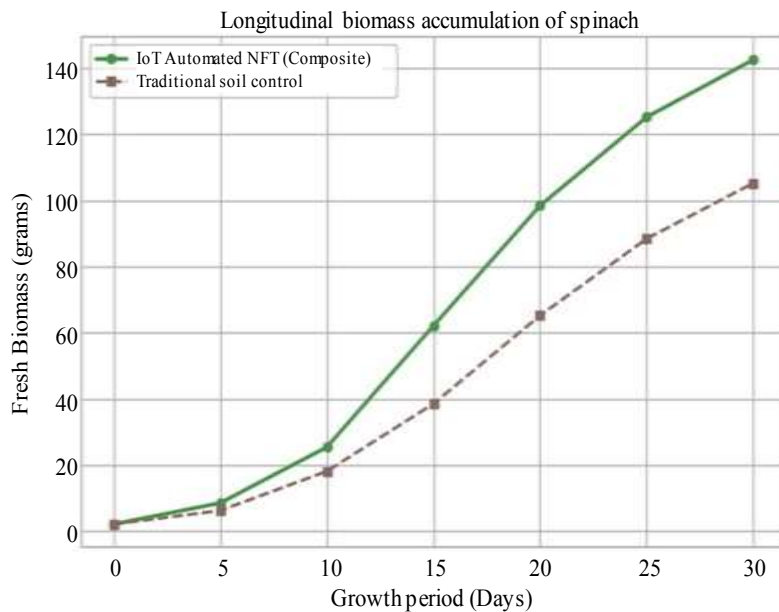
- *Data-driven yield optimization:* By using the MING stack architecture, industrial growers can shift from manual labour to high-precision automation. This cuts down on human errors in nutrient management.
- *Modular scalability:* The lightweight LECA-Perlite-Coir composite is perfect for rooftop farming and urban skyscrapers, where the weight of traditional soil poses a structural issue.

**Table 2.** Comparative performance matrix.

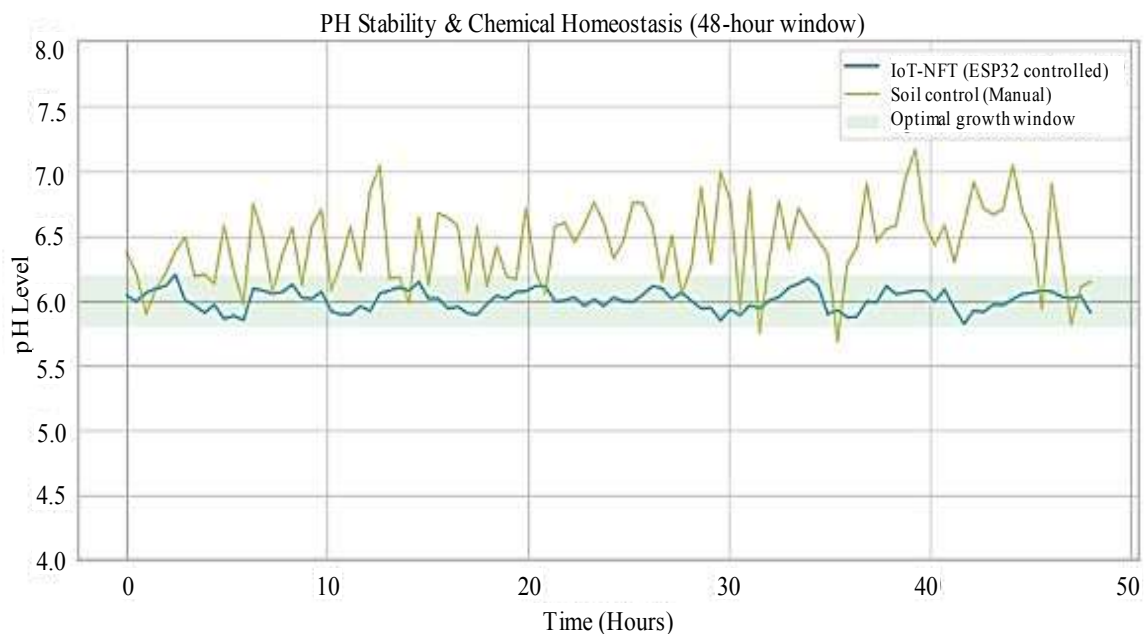
Parameter	IoT-Automated NFT (Composite)	Traditional Soil Control	Improvement (%)
Avg. Fresh Biomass (g)	142.5	105.2	+35.4%
Leaf Area Index (LAI)	4.82	3.15	+53.0%
Water Consumption (L)	4.2	38.5	-89.10%
Nutrient Stability (pH)	$\pm 0.15$	$\pm 0.8$	+81.2%



**Figure 6.** Comparative water-use efficiency (WUE) for IOT-NFT composite and conventional farming using soil in terms of biomass produced gram per liter.



**Figure 7.** Growth Period in terms of days with respect to fresh biomass in grams.



**Figure 8.** Real-Time pH stability in hours and chemical homeostasis in terms of pH level for three different conditions.

### Integration with Industry 4.0 Standards

This project acts as a working model for Industry 4.0 in agriculture, often called Agriculture 4.0:

- *The digital twin concept:* The real-time data flow from the ESP32 to Influx DB allows for the creation of a “Digital Twin” of the crop. Industrial facilities can use this to run simulations, accurately predicting harvest dates and resource needs.
- *Interoperability and MQTT:* By using the MQTT protocol, your system can communicate with other industrial machines. This creates a decentralized network of smart farms that share data to improve regional water and electricity use.

### Sustainable Development and the Circular Economy

This work directly supports the United Nations Sustainable Development Goals (SDGs) by turning agricultural “waste” into industrial “wealth”:

- *Waste-to-resource (SDG 12)*: By using Coco Coir and Cocopeat, by-products of the coconut industry, your project shows a circular supply chain that reduces the environmental impact of substrate production.
- *Water scarcity mitigation (SDG 6)*: In areas facing serious water shortages, the 89.1% reduction in water usage documented in this study offers a viable model for sustainable food production.

### Industrial Substrate Manufacturing

The physical and morphological tests used in this project, especially the porosity and WHC testing, create a model for the industrial production of specialized growth media.

- *Custom composites*: Manufacturers can use your 2:1:1:1 volumetric ratio to mass-produce lightweight, high-porosity substrates for commercial hydroponics, replacing non-renewable materials like Rockwool with your sustainable lignocellulosic-polymeric option.

### CONCLUSION

The combination of engineered multiphase composites and IoT-driven automation has created a precise framework for urban agriculture. This research presents its findings through the following key pillars:

- *Engineered material composition*: A custom 2:1:1:1 volumetric composite of LECA, Perlite, Coco Coir, and Cocopeat formed a gradient-porosity matrix. This design kept total porosity between 75% and 85%, effectively preventing substrate compaction and ensuring continuous oxygen flow to the root zone during the 30-day trial.
- *IoT-driven chemical homeostasis*: The ESP32-based “Perception-to-Actuation” model created a reliable digital nervous system. Using the MING stack for real-time monitoring, the system-controlled pH and TDS levels with much greater accuracy than manual geotropic methods, maintaining a stable nutrient environment.
- *Improved biological yield*: The combination of automated precision and the sorption-desorption kinetics of the lignocellulosic fibers produced better growth results for *Spinacia oleracea*. Compared to the soil control group, the system showed a 35.4% increase in fresh biomass and a 53% rise in Leaf Area Index (LAI).
- *Resource efficiency and sustainability*: The recirculating hydraulic design achieved an 89.1% reduction in water use. This outstanding water-use efficiency, along with recycling agricultural waste into high-performance growth media, ensures the project meets international sustainability standards, specifically SDG 6 and 12.

### Future Scope

In the prospective development of this system, one should highlight that the emphasis will be placed on the shift towards autonomous operation with predictive control based on Physics-Informed Neural Network (PINN) training on data accumulated in the MING stack during the cultivation process. In particular, PINNs can be used to proactively manipulate nutrient dosing rates and pH values depending on crop-specific metabolism at different phenological stages of growth. At the same time, advances in material science could be associated with lignocellulosic fibers’ surface modification via applying biodegradable polymers, such as polylactic acid (PLA), to improve their thermo-mechanical properties. Finally, to achieve additional objectives associated with promoting sustainability and food security, this model is ready to be modified for high-density vertical farms. Specifically, one may explore how solar panels can be utilized in order to provide clean electricity for ESP32 microcontrollers and hydraulic pumps. Therefore, one would create an entirely carbon neutral cultivation module. As for the fully

circular approach, one might consider using harvested spinach biomass as filler agents to develop new bio-composites as the substrates. Thus, there will be no waste left after completing the growing cycle, while dependence on raw natural resources will be reduced. Further trials could involve fruiting plants that accumulate larger quantities of biomass.

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