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Development of a Hydroponic System for Laboratory Rice Cultivation under 29 Nutrient Variation Treatments in a Greenhouse Environment

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ABSTRACT

This research discusses the creation and evaluation of an IoT-enabled hydroponic system built for controlled laboratory production of rice under 29 nutritional variation treatments within a greenhouse setting. The system featured automated watering, real-time monitoring, and continuous data logging to adjust temperature, humidity, pH, and electrical conductivity, ensuring exact environmental and nutrient control. Sustainable substrates such as coco peat and rice husks were applied to offer optimum aeration and moisture retention. Twenty-nine fertilizer recipes with different levels of N, P, and K were tried on the Farro 44 variety of rice and monitored for growth, tillering, and production as per fertilizer rates. Research indicated that plants receiving well-balanced formulas of N:P:K values of 10.50:5.25:10.50 ppm and 14:7:14 ppm were conducive for healthy vegetative growth, maximum

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tillering, and optimal production at 93 g per pot. Treatment with inadequate amounts caused a hold on growth with chlorosis and reduced biomass. The IoT-based control system made better use of water and nutrients and showed that hydroponic methods were good for precision farming. The research identifies and emphasizes the feasibility and efficacy of combining controlled hydroponics with IoT as an approach toward streamlined nutrient and water utilization for successful production. The use of solar energy and AI technology would be an area worth exploring for research on the large-scale implementation of intelligent hydroponic systems.

Keywords: Hydroponics; IoT Monitoring; Nutrient Optimization; Rice Cultivation; Controlled Environment; Sustainable Agriculture

1. Introduction

Hydroponics refers to a method conducted on plants with no soil and an environmentally friendly approach. It employs nutrient solutions, which are water-based. Therefore, it is an environmentally friendly method conducted on plants with consideration for impacts on the environment, sustainability, and adjusting to changes within climatic conditions^[1-3]. There have been various suggestions on how hydroponic farming might solve food insecurity on a global scale. Various research papers have shown that hydroponic farming might result in improving the environment, food more stable and safer, and promoting sustainable agriculture practices^[4,5]. Since hydroponic farming has controlled growing conditions, modern hydroponic farming enables farmers to have a harvest every day and within a shorter period and with lesser space. Consequently, regardless of prevailing weather conditions, soil fertility, or land availability for agriculture, hydroponic farming will increase crop production^[6].

It should be noted that hydroponics requires fewer resources, including land, pesticides, and water, compared to open-field farming. Moreover, it often experiences biotic and abiotic stresses, which reduce crop production. Typically, hydroponic production occurs within greenhouses. These have enabled growers to control factors such as temperature, relative humidity, light, and CO₂. It should be added that hydroponics allows plants to be grown for a more prolonged period^[7-11]. Hydroponically grown plants, signified by hydroponicus, possess a constant and equal supply of water and nutrients. It should be added that this method represents the best technique for growing and developing plants, given that

the controlled atmosphere and temperature allow for perfect control over critical factors like temperature, humidity, light intensity, and air movement. Consequently, it ensures that plants are as productive and stress-free as possible. Typically, most hydroponic production systems occur within heated greenhouses. It should be noted that due to these conditions, plants can be grown throughout the year. Moreover, they can be grown irrespective of prevailing weather conditions. Also, these heating systems will allow people to have more food. Moreover, it will be possible for more food to be available within the market. To satisfy plants' demand for an optimal amount of vital nutrients and achieve maximum production, it should be added that hydroponic production systems precisely control nutrient composition. It should be added that electrical conductivity and pH levels monitor and control nutrient intensities and proportions. Typically, these factors provide critical information on nutrient intensities and composition. It should be noted that maintaining optimal EC levels ensures that plants receive the necessary nutrients in adequate amounts without risking over-saturation. Moreover, optimal control of pH levels enables optimal nutrient dissolution and optimal nutrient absorption. It should be added that it is possible to obtain optimal food production, optimal food quality, and reduced dependence on conventional farming methods due to these hydroponic production systems and heated greenhouses^[12-16].

Rice (*Oryza sativa*) has become one of the most important staple foods in the world. It is a big part of the overall consumption trend in the West African region and of the dietary habits and food consumption patterns of people all over the world^[8]. Rice used to be a luxury food, but now it is a common food that most Nigerians eat ev-

ery day. Asia, Sub-Saharan Africa, and South America are the greatest places where people eat rice, which is one of the most important staple foods in the world^[17,18].

More than half of the people on Earth rely on it for about 80% of their food needs (21). According to *statista*, the world ate about 523.8 million metric tons of rice in the crop year 2023/24. Nigeria is among the greatest consumers, producers, and importers of rice. The quantity they consumed in 2018 stood at 6,900,000 metric tons, which surpasses that of any other country. Nigeria imports large quantities of rice from Thailand, China, and India due to its milled rice amounting to 1.8 million tons^[19,20]. To solve the rising demand for rice consumption, we should adopt sustainable approaches and develop new ideas. As more Nigerians turn towards consuming more rice, it shows a major shift in people's food. Before rice became popular as a Nigerian food product, Nigerians typically depended on more traditional staples, such as cassava, maize, and yam. Traditional Nigerian cultures and agricultural settlements have highly valued these as major staples. Lifestyle changes, city migration, and food diet changes have highly promoted rice as an alternative food source among Nigerians (Global Rice Science Partnership^[21,22]). Increased rice consumption patterns among people also indicate changes within an emerging nation like Nigeria. As Nigeria experiences an increase in its population and an uptrend in its urban migration rate, there's also an equal uptrend in demands for food sources that are highly accessible and convenient. As a result, rice became Nigeria's main food, with higher consumption volumes rising on an annual basis. Despite rising demands within Nigeria, an increase represents major problems within the country's agriculture. It will be very challenging, as it would rely on an importation option because Nigeria doesn't produce a considerable amount of rice. As a result, it ends up with economic impacts because it runs out of foreign currencies and an exposed low value within global markets. As a result, rice has become a crucial component of Nigeria's agricultural and foreign food security initiatives and guidelines^[23-25].

1.1. Problem Statement

Rice is a staple food crop of global importance, but its growth and development efficiency is still hampered

by a lack of knowledge about interactions between crops and nutrients in controlled growth environments. The common rice growth system is highly affected by factors such as soil variability, water variability, and environmental variability, making it very difficult to gauge the effect of individual and combined amounts of necessary nutrients for enhanced growth and development. This matter is particularly evident in growth environments such as laboratories and greenhouses, where precision is paramount^[26].

A promising solution in this area comes from hydroponic experiments; nevertheless, the major issue in hydroponic experiments conducted on rice is the limited range in which the nutrients are measured. Currently, there is a shortage of hydroponic platforms that are able to test the variation of the nutrients within a wide scope while conserving a constant environment. Such deficiency impedes the creation of robust datasets in the area of optimizing nutrients^[27].

In addition, a standard hydroponic setup for growing rice plants in a laboratory is not available. Therefore, mimicking a practical level of nutrient stress and nutrient availability within a controlled laboratory setting is challenging. Such an issue poses a challenge in conducting comparative research, reproducing research in different laboratories, or developing a precision strategy for growing rice in either a greenhouse or open field.

Thus, it is imperative that a controlled hydroponic setup be especially designed for rice growth in a lab setting that would be capable of handling more than one nutrient variation simultaneously. This would allow researchers to meticulously alter and track nutrient variations, systematically analyze rice reaction factors for 29 different nutrient variations, and establish a scientifically sound setup for enhanced research in nutrient efficiency.

1.2. Research Gap

Despite the worldwide significance and importance of rice as a staple food crop, the actual interaction and effect of various levels of essential nutrient requirements and conditions during controlled environmental conditions and growth cultures remain unclear. As conventional and normal crop cultivation involves numerous

complicated and complex factors influenced by the variability and differences in soils and environmental conditions, precise and exact assessments and measurements remain challenging and difficult, making it hard and impossible from yielding exact and precise results and definitions related to crop growth and development due to limitations on essential nutrient requirements and conditions posed and created by conventional and normal crop cultivation methods on soils and environmental conditions and factors influencing and affecting crop development and growth due to lack and absence of controlled and standardized crop development and environmental conditions on soils and environmental conditions and factors that influence and affect crop development and growth due to differences and gaps created by conventional and normal crop cultivation methods on soils and environmental conditions and factors influencing and affecting crop development and growth on conventional and normal crop cultivation methods on soils and environmental conditions and factors affecting crop development and growth due to conventional and normal crop cultivation methods on soils and environmental conditions and factors influencing and affecting crop development and growth due to conventional and normal crop cultivation methods and conditions on soils and environmental conditions and factors influencing and affecting crop development and growth due to conventional and normal crop cultivation methods and conditions on soils and environmental conditions and factors influencing and affecting crop development and growth due to conventional and normal crop cultivation methods and conditions on soils and environmental conditions and factor.

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various levels and ranges and requirements and conditions of essential and increased levels and requirements on crop development and growth due.

1.3. Theoretical/Conceptual Frame Work

This research is based on theories of plant nutrition, controlled environment agriculture, and crop responses modeled from systems theory, which together provide a scientific understanding of growth and performance responses in rice.

Plant nutrition theory illustrates that rice growth and development require the well-rounded supply of macronutrients and micronutrients that serve crucial functions primarily during photosynthesis, enzyme functioning, the composition of cells, and metabolic processes. Doses of the involved nutrients that cut across the deficiency, sufficient, and toxic levels affect plant growth and development factors that include shape, chlorophyll, root growth, and physiological efficiency.

The controlled environment agriculture theory assumes that plant responses can be better quantified if factors like temperature, relative humidity, intensity of illumination, and nutrient availability are carefully controlled. Hydroponic systems behave in a similar manner, as they eliminate soil variability and allow control of nutrient content or concentration and administration to plants in a manner such that the plant response recorded is directly related to the nutrient administered to plants.

In this experiment, the hydroponic system is used as the treatment platform and provides 29 different treatments for nutrient variation. With the addition of IoT-based monitoring capabilities, there can be a continuous and real-time measurement of key parameters in the hydroponic system, such as pH, EC, temperature, and flow rate of the nutrient solution. Additionally, environmental factors in the greenhouse can also be monitored.

The intermediate variables are important physiological responses of plants that are regulated by nutrient supply and environmental control, such as efficiency of nutrient uptake, leaf growth, root characteristics, rate of growth, and stress responses. The efficiency of these responses determines the values of the dependent variables, which are plant height, biomass, phenological development, or overall nutrient use efficiency.

Environmental factors in the greenhouse serve as moderating variables that guarantee that plant responses are traceable to the experimental nutrient treatments and not to environmental variability. With nutrient management, IoT capabilities, and environmental control, there is a conceptual frame of reference whereby precise control of nutrients results in measurable outcomes in rice growth.

Such an approach supports the hypothesis that optimized nutrient conditions, continuously monitored and adapted through the use of IoT technologies, could lead to improvements in growth parameters, nutrient

use efficiencies, and reproducibility results with respect to experimentation. Moreover, the proposed work will give practical applications and solutions for sustainable rice farming.

2. Materials and Methods

This chapter describes in a detailed manner the research methods and materials that have been adopted. The chapter contains information about the experimental setup, procedures adopted, and methods adopted for analysis of data as shown in **Figure 1**.

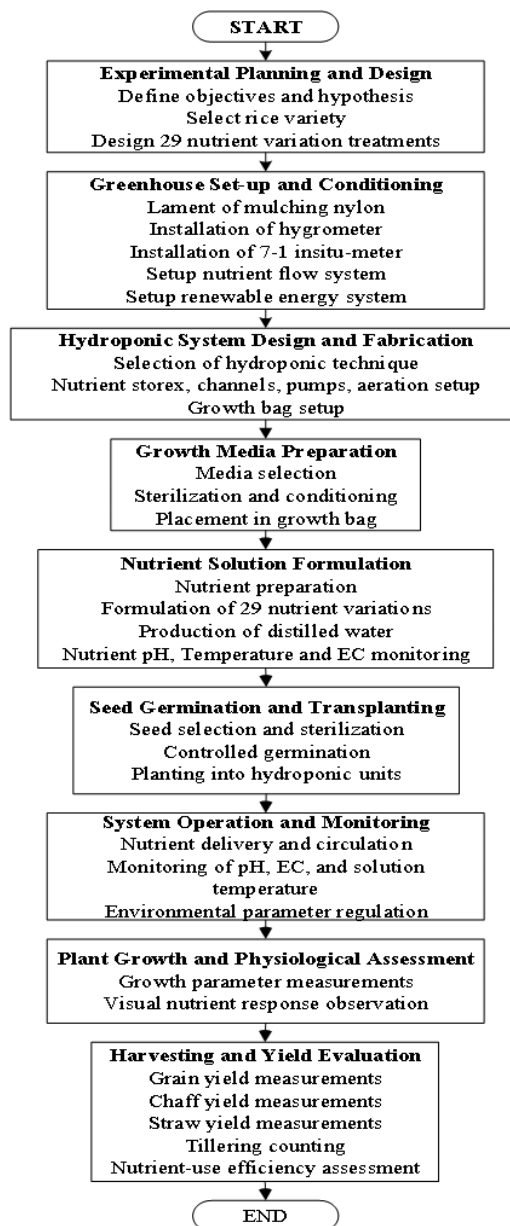


Figure 1. Research Methodology Flow Chart.

2.1. Preparing the Greenhouse

The experiment took place within a greenhouse at the National Centre for Agricultural Mechanization in Ilorin.

The greenhouse had a sophisticated watering system that operated based on a predefined schedule. This and various other technologies were incorporated to assure that all treatment groups have equal hydration levels and reduce water loss as a result of watering. The importance of water scheduling and control within a micro pump and drip line feeding system cannot be underestimated, as it plays a critical role in growing hydroponic rice with varying nutrient levels. In this connection, there was an IoT-based soil monitoring system through which factors like the electrical conductivity, pH value, temperature, and fertilizer content within the soil were continuously tracked. Based on cloud storage and simultaneous tracking, identification of soil status could be done to act accordingly. The IoT-powered hygrometer in the greenhouse tracked the temperature and humidity both inside and outside every hour. As a result, it was possible to monitor the weather systematically. This technique facilitated the maintenance of a consistent microclimate. This is very vital for rice growth.

2.2. Soil for Planting

We selected coco peat and rice husk as the prime media for growing because they are ecofriendly and have outstanding water retention and aeration. Both these materials are apt for roots because they maintain optimal water content and allow satisfactory air passage.

Hydroponic growth requires optimal development and nutrient uptake capacity on the part of the roots.

Coco peat is obtained from the fibrous coat of coconuts. It is light, reusable, and biodegradable. On the contrary, rice husk acts as an agricultural waste product, which maintains the stability of mediums and supports easy draining. Together, they form a medium that is highly efficient and ecofriendly. The mediums were sterilized before use, killing all germs, fungi, and microorganisms, which might inhibit the growth of plants. The hydrogen peroxide (H₂O₂), a 35% solution, was used because it is a highly oxidizing agent that removes dirt from organic matter without leaving behind any harmful substance. The sterilized region was free from germs, thus facilitating easy growth for the seedlings. The pH level of the mediums, which was measured after sterilization, was recorded at 5.1. It was assumed that it should be at an optimal height for growing rice under aquatic mediums. A slightly low pH value within soils plays a significant role because it boosts nutrient intake within plants. It guarantees healthy growth and increases production capabilities within plants. Processing methods made mediums completely safe for living organisms and made them chemically balanced as a result, promoting soilless rice cultivation.

2.3. Nutrient Solutions

Various nutritional solutions were formulated with 29 different nutrient formulas. The nutrient formulas were differentiated based on varying N, P, and K percentages, while Ca, Mg, and micronutrients Zn, Fe, Mn, Cu, Mo, and B percentages were kept constant. A 1000 ppm nutrient solution was formulated using an appropriate compound as shown in **Table 1**. **Tables 2** and **3** show the daily fixed and varying nutrient consumptions per day per 29 planting bags.

Table 1. Nutrients and the compound extracting it from.

| S/No. | Element | Compound |
|-------|---------|--|
| 1 | N | NH ₄ Cl ₂ |
| 2 | P | Na ₃ PO ₄ |
| 3 | K | KCl |
| 4 | Ca | CaCl ₂ |
| 5 | Mg | MgCl ₂ |
| 6 | Zn | ZnCl ₂ |
| 7 | Fe | FeCl ₃ |
| 8 | Mn | MnSO ₄ |
| 9 | Cu | CuCl ₂ |
| 10 | Mo | (NH ₄) ₂ MoO ₄ 4H ₂ O |
| 11 | B | H ₃ BO ₃ |

Table 2. The fixed nutrients that constant in all 29 planting bags.

| S/No. | Fixed Nutrients | Daily Required |
|-------|--|----------------|
| 1 | CaCl ₂ | Ca: 7 |
| 2 | MgCl ₂ | Mg: 3.5 |
| 3 | ZnCl ₂ | Zn: 0.7 |
| 4 | FeCl ₃ | Fe: 1.5 |
| 5 | (MnSO ₄) | Mn: 0.7 |
| 6 | (NH ₄) ₂ MoO ₄ 4H ₂ O | Mo: 0.06 |
| 7 | H ₃ BO ₃ | B: 0.7 |
| 8 | CuCl ₂ | Cu: 0.3 |

Table 3. The Varied nutrients across the 29 planting bags.

| S/No | Pot Number | Nutrient (S) | Daily Required (ppm) |
|------|------------|--------------|----------------------|
| 1 | 1 | N | 14 |
| 2 | 2 | N | 10.50 |
| 3 | 3 | N | 7 |
| 4 | 4 | N | 3.50 |
| 5 | 5 | P | 7 |
| 6 | 6 | P | 5.25 |
| 7 | 7 | P | 3.5 |
| 8 | 8 | P | 1.75 |
| 9 | 9 | K | 14 |
| 10 | 10 | K | 10.50 |
| 11 | 11 | K | 7 |
| 12 | 12 | K | 3.50 |
| 13 | 13 | N; P | 14; 7 |
| 14 | 14 | N; P | 10.50; 5.25 |
| 15 | 15 | N; P | 7; 3.5 |
| 16 | 16 | N; P | 3.50; 1.75 |
| 17 | 17 | N; K | 14; 14 |
| 18 | 18 | N; K | 10.50; 10.50 |
| 19 | 19 | N; K | 7; 7 |
| 20 | 20 | N; K | 3.50; 3.50 |
| 21 | 21 | P; K | 7; 14 |
| 22 | 22 | P; K | 5.25; 10.50 |
| 23 | 23 | P; K | 3.50; 7 |
| 24 | 24 | P; K | 1.75; 3.50 |
| 25 | 25 | N; P; K | 14; 7; 14 |
| 26 | 26 | N; P; K | 10.50; 5.25; 10.50 |
| 27 | 27 | N; P; K | 7; 3.50; 7 |
| 28 | 28 | N; P; K | 3.50; 1.75; 3.50 |
| 29 | 29 | N; P; K | 0; 0; 0 |

2.3.1. Nutrient/Water Container

For the experiment, a set of 20 different plastic containers was set up, each serving as one treatment unit of nutrient application. Each container received an accurately composed nutritional solution to represent different levels of nitrogen (N), phosphorus (P), and potassium (K) according to the experimental design. This method, with every treatment, a distinct nutritional environment was created for the growth of the rice plants to facilitate the measurement of the effect caused by the varying amounts of macronutrients. The use of identical dimensions of the containers facilitated the control of the volume and minimized cross-contamination, thus ensuring that the compar-

isons were accurate.

2.3.2. Thermometer

The temperature of the nutrient solution and the water, therefore, was assessed and confirmed with a thermometer before the commencement of every watering procedure. This measure is particularly significant with the intention of ensuring that the solution is at a temperature ideal for nutrient uptake. In a hydroponic setup, temperatures are essential, with high temperatures resulting in a decline in oxygen, hence a negative impact on root respiration, while low temperatures result in a negative impact on metabolism rates and nutrient absorption.

2.3.3. Procedures for Producing Distilled Water

In our experiments, a common laboratory distillation technique is used to verify that the distilled water is highly purified with no impurities, salt, or other components that might affect nutrient preparation. Distilled water is used to make all the required chemical solutions for the growth of rice in the greenhouse. In our research, the use of distilled water helps keep the purity of the nutrients untouched, making sure that the quality is consistent for all the treatment solutions. The process reduces the formation of minerals, which is common with normal water sources, thus affecting the pH and electric conductivity. This step is necessary because nutrient preparation is precisely measured for ideal plant growth in a hydroponic setup.

2.4. Hydroponic System Design

The planting bag technique was used in the arrangement of the culture to provide a confined and organized environment for the root growth and nutrient supply of the plants. The bottom of the planting sacks was lined with granite, up to a depth of 5 cm from the bottom, for drainage purposes to prevent accumulation of water in the sacks, which might affect aeration in the root environment. Above the layer of granite was a 25-cm-thick layer of the actual growing medium, which was a mixture of coco peat and rice husk, because of their excellent water retention, aeration properties, and environmentally friendly characteristics. Each nutrition treatment was supplied through a drip irrigation line connected to a respective bag to ensure that the exact amount of all nutrient solutions was delivered directly to the plants that were assigned to a particular treatment. This configuration has effectively avoided cross-contamination among the treatments and preserved the experimental design's integrity for the proper assessment of the various nutrient formulation effects on rice growth performance.

2.5. Planting and Growing Rice Seeds

Seedlings used in this experiment were the Farro 44 rice variety. Seeds were soaked in water for 24 h, drained, and put in an impermeable nylon bag for an-

other 24 h to sprout. The inoculant was applied to the sprouted seed, which was then planted directly into the growing medium at 25 mm depth.

2.6. Data Collection

We measured some of the key agronomic parameters of plant height, tiller number, crop yield, and straw weight to determine rice plants' growth performance and productivity. A previously calibrated measuring scale was used to measure plant height from the base of the stem at the soil surface to the apex of the tallest panicle. For this research, the measurement was done at different times and over the course of various developmental stages to see how changes in nutrition would affect vertical growth. We conducted a count of the actual number of tillers during the peak of tillering for each plant; this is essentially done to determine the health and productivity of such plants, as the higher the count of tillers, the greater the proportion of cereal grown. Afterwards, the panicles from each treatment were threshed, their grains washed and dried in an oven up to constant moisture, while a precision digital scale was utilized to weigh the grains to determine an estimate of the yield. The straw weight was determined from the remaining above-ground biomass, not including grains, that had been dried in an oven. The results included the entire vegetative mass and efficiency of nitrogen use by the plants. Generally, the group growth properties offered a snapshot of rice plant morphology, productivity, and reaction to different nutrient conditions.

3. Results

This section provides the findings of the research.

3.1. System Stability

The IoT-based system, during the experiment, provided a stable microclimate, which is evident from the temperature measurement of 28 °C to 33 °C and relative humidity of 68% to 79%. The pH was stable in the range of 5.5–6.3, while the electrical conductivity (EC) was within optimum ranges (1.5–2.2 mS/cm), indicating adequate nutrient supply.

3.2. Results on Effects of Daily Varied NPK Nutrient Applications on Rice Growth and Yield Parameters under Controlled Hydroponic Conditions

Table 4 summarizes the growth and yield performance of rice plants under different combinations

of N, P, and K nutrient concentrations in ppm. Each POT represents (1 to 29) a different treatment combination used every day during the cultivation period. The agronomic characteristics studied are plant height (cm), grain weight (g), straw weight (g), and number of tillers.

Table 5 does show the summary of average growth performance across nutrient groups.

Table 4. Yield Response of The Varied nutrients Rice.

| POT No. | Daily Varied Applied Nutrients N:P:K (ppm) | Plant Height (cm) | Grains (g) | Straw (g) | Tillering (No.) |
|---------|--|-------------------|------------|-----------|-----------------|
| 1 | 14:0:0 | 28 | 52 | 26 | 15 |
| 2 | 10.50:0:0 | 27 | 50 | 25 | 14 |
| 3 | 7:0:0 | 27 | 49 | 25 | 14 |
| 4 | 3.50:0:0 | 26 | 47 | 23 | 13 |
| 5 | 0:7:0 | 13 | 28 | 14 | 8 |
| 6 | 0:5.25:0 | 12 | 27 | 14 | 8 |
| 7 | 0:3.5:0 | 11 | 22 | 11 | 6 |
| 8 | 0:1.75:0 | 11 | 21 | 10 | 6 |
| 9 | 0:0:14 | 14 | 28 | 14 | 8 |
| 10 | 0:0:10.50 | 14 | 27 | 14 | 8 |
| 11 | 0:0:7 | 13 | 27 | 13 | 7 |
| 12 | 0:0:3.50 | 12 | 21 | 11 | 6 |
| 13 | 14:7:0 | 15 | 31 | 16 | 9 |
| 14 | 10.50:5.25 | 15 | 32 | 16 | 9 |
| 15 | 7:3.5 | 15 | 29 | 14 | 8 |
| 16 | 3.50:1.75 | 14 | 28 | 14 | 8 |
| 17 | 14:14 | 29 | 65 | 32 | 18 |
| 18 | 10.50:10.50 | 28 | 64 | 31 | 18 |
| 19 | 7:7 | 28 | 62 | 30 | 17 |
| 20 | 3.50:3.50 | 27 | 61 | 30 | 17 |
| 21 | 7:14 | 30 | 62 | 30 | 17 |
| 22 | 5.25:10.50 | 29 | 62 | 29 | 17 |
| 23 | 3.50:7 | 28 | 58 | 28 | 16 |
| 24 | 1.75:3.50 | 28 | 58 | 28 | 16 |
| 25 | 14:7:14 | 32 | 93 | 46 | 26 |
| 26 | 10.50:5.25:10.50 | 32 | 93 | 46 | 26 |
| 27 | 7:3.50:7 | 31 | 90 | 44 | 25 |
| 28 | 3.50:1.75:3.50 | 31 | 87 | 42 | 24 |
| 29 | 0:0:0 | 9 | 0 | 3 | 2 |

Table 5. Summary of Average Growth Performance Across Nutrient Groups.

| Nutrient Group | Average N:P:K (ppm) | Average Grain Weight (g) | Average Straw Weight (g) | Average Tillers (No.) | Average Plant Height (cm) | General Growth Observation |
|----------------|---------------------|--------------------------|--------------------------|-----------------------|---------------------------|---|
| N-only (1-4) | 8.5:0:0 | 50 | 25 | 14 | 27 | Moderate vegetative growth but healthy leaves and fewer panicles |
| P-only (5-8) | 0:4.4:0 | 25 | 12 | 7 | 12 | Poor growth; spindly stems and sparse foliage |
| K-only (9-12) | 0:0:8.5 | 26 | 13 | 7 | 13 | Dwarfing height; enhanced stiffness of the stem but poorly filled panicle |
| N-P (13-16) | 8.0:4.6:0 | 30 | 15 | 9 | 15 | Moderate tillering; improved leaf color and canopy formation |
| N-K (17-20) | 8.0:0:8.0 | 63 | 31 | 17 | 28 | Strong vegetative growth; high tillering; early panicle initiation |
| P-K (21-24) | 0:4.6:8.0 | 60 | 21 | 17 | 29 | Healthy canopy, enhanced root structure, and good tillering |
| N-P-K (25-28) | 8.5:4.4:8.5 | 90 | 45 | 25 | 32 | Optimal growth; Maximal yield and accumulation of biomass |
| Control (29) | 0:0:0 | 0 | 3 | 2 | 9 | Highly dwarfed; pale leaves with limited development |

4. Discussion

The experimental findings show that NPK ratios have a significant effect on rice growth and productivity. Nitrogen is most welcome in the case of vegetation, phosphorus promotes root development and energy, and potassium helps plants to combat stress and matureness. The result of NPK ratios has been in line with the findings of previous research by Shubham et al.^[21], which depicts that plants grow with increased biomass and productivity with optimized nutrient ratios. The IoT-based technology has facilitated real-time observation of the environment and smart irrigation systems, which meets the definition of precision agriculture^[7]. Coco peat and rice husk were an eco-friendly and economical growing medium. It also favored root aeration and microbial stability. Hydroponic rice under this study was faster growing, more uniform in shape, and superior in yield attributes when compared with soil-grown rice plants, confirming the above-mentioned findings of Khan^[7]. Such results confirm that hydroponic systems are suitable models for crop nutrient studies at a laboratory scale and future food production in controlled atmospheres.

4.1. Growth Performance

A total of 29 nutrient treatment pots were assessed for their respective daily amounts of nitrogen (N), phosphorus (P), and potassium (K) as described in **Table 1**. The nutrient treatments were grouped into four categories: single-nutrient applications comprised Pots 1–12; two-nutrient combinations, Pots 13–24; full NPK combinations, Pots 25–28; and the control without N, P, or K, Pot 29. Pot 25 was considered the highest control since it contained the highest amount of nutrients. On the other hand, Pot 29 was considered the lowest control with no added nutrient content. The levels of micronutrients remained the same across all the treatments, while that of macronutrients varied from 0 to 14 ppm. This procedure was done to ensure that any variability in the growth of plants would be based on changes in NPK alone.

Mean differences among the treatments were statistically significant at $p < 0.05$, indicating that the

types of nutrients and dosage rate hugely affected plant growth. Plants that had received a complete and proper supply of nutrients had an enormously high growth rate compared to those that received either excessive or insufficient nutrient supplies. Pot 25 (N:P:K = 14:7:14 ppm) and Pot 26 (N:P:K = 10.50:5.25:10.50 ppm) showed the healthiest growth of plants in these containers. Their health was evidenced through highly formed stems, plenty of foliage, and high-banked plants. Plants in Pot 26 also showed the tallest average height of 93.4 cm, which means that a moderate amount of fertilizer used favored the greatest growth of the plants.

The control treatment (Pot 29; N:P:K = 0:0:0 ppm) was the most inferior in growth. Plants exhibited marked symptoms of nutritional deficiency, such as chlorosis, and measured 47.2 cm in height. It follows from the above that satisfactory nutrition availability determines the improvement in plant strength. Comprehensive and well-balanced formulas of NPK have made a tremendous difference against incomplete or nutrient-less treatments.

The application of a balanced NPK ratio of 10.50:5.25:10.50 ppm yielded the best development performance. For the 0:0:0 ppm treatment without fertilizers, the poorest growth performance was documented. There were significant growth differences among all treatments, emphasizing that optimum crop development depends on a proper supply of all macronutrients.

4.2. Discussion on the Fixed Nutrients and Their Effects

The micronutrient supply of all 29 pots was kept constant to meet the needs of various physiological functions that occur under normal conditions, including chlorophyll synthesis, enzyme activation, and structural integrity. Specifically:

- (1) Calculated amount of Calcium (Ca, 7 ppm): It offers assistance for cell wall strength and root growth.
- (2) Magnesium (Mg, 3.5 ppm) works as the core atom in chlorophyll, supporting photosynthesis.
- (3) Zinc, Zn, 0.7 ppm: participates in the synthesis of enzymes and in auxin metabolism.
- (4) Iron (Fe, 1.5 ppm) This element is necessary for

chloroplast growth and respiration.

- (5) Mn (Manganese, 0.7 ppm): Participates in photosystem II and oxidative stress tolerance.
- (6) Molybdenum (Mo, 0.06 ppm) is required for nitrate reduction and nitrogen metabolism.
- (7) Boron-B (0.7 ppm) is involved in cell wall production and reproductive development.
- (8) Copper Cu 0.3 ppm Participates in lignin production and is also an enzyme cofactor.

With micronutrients held constant, the experiment isolates the effect of the macronutrient on yield quite efficiently; therefore, any differences in performance emerge largely from N, P, and K variances.

4.3. Discussion of the Varied Nutrients (NPK) and Their Effects

The NPK variance across the 29 treatments (pots) shows an increasing complexity in nutrient interactions, from single-element treatments to dual combinations and, finally, the full NPK combination.

1. Single-Nutrient Treatments (Pots 1–12)
 - i. Nitrogen alone Pots 1–4: Rice yield increased across higher levels of N application. The highest N 14 ppm, Pot gave 52 g of grains, 26 g of straw, and 15 tillers, while the lowest N (3.5 ppm) pot yielded 47 g of grains, 23 g of straw, and 13 tillers, thus showing nitrogen's high role in encouraging vegetative growth and tillering.
 - ii. Phosphorus alone (pots 5–8): Lower yields were recorded, where from 28 g of grains at 7 ppm P, the yields decrease to 21 g of grains at 1.75 ppm P. Tillering, however, ranged between 6 and 8. This showed that while P enhances root and reproductive development, the solo effect is limited without extra N.
 - iii. Potassium alone (Pots 9–12) showed similar yield patterns to those observed with phosphorus: 28 g of grains at 14 ppm K dropped to 21 g of grains at 3.5 ppm. Potassium had a mild effect, supporting stalk

strength but not enough for high grain yield per stand.

2. Dual-Nutrient Applications (Pots 13–24)
 - i. N + P (Pots 13–16): There existed a moderate increase in improvement compared to the single-nutrient setups. The highest N:P ratio of 14:7 ppm yielded 31 g of grains with 9 tillers. This showed the synergistic effect in the development of root establishment and nutrient assimilation.
 - ii. N + K in pots 17–20: This treatment revealed a significant increase in yield with 65 g grains, 32 g straw, and 18 tillers at 14:14 ppm. This trial conveyed the importance of nitrogen for tillering, as well as potassium for the translocation of photosynthates.
 - iii. P + K (Pots 21–24): Grain yield was similar, with a yield of 58–62 g of grains, while the tiller number was 16–17, evidencing the complementary function of P + K in energy transfer and carbohydrate metabolism.
3. Triple-Nutrient (N + P + K) Treatments (Pots 25–28)

The following are the treatments that produced the best yield performance based on all factors: The composition of Pot 25 was 14:7:14 ppm, while Pot 26 had a composition of 10.50:5.25:10.50 ppm; in both cases, there were 93 g of grains and 46 g of straw.

Even the lowest concentration of NPK, which is 3.5:1.75:3.5, was still capable of supporting high yields with respect to grains of 87 g, straw of 42 g, and 24 tillers. This, therefore, indicates that there is a high synergy when all three components are provided, resulting in increased photosynthesis, energy transmission, and growth.
4. Control (Pot 29, 0:0:0 ppm)

The control, which lacked all forms of macronutrients, produced no grains, only 3 g of straw, and only 2 tillers, indicating that nutrient limitation plays a significant role in limiting rice growth.

The results indicate a positive relationship between nutrient balance and rice production perfor-

mance.

- (1) Nitrogen is required by the plants for tillering and leaf area expansion.
- (2) Phosphorus enhances the development of roots and the formation of grain.
- (3) Potassium regulates the balance of water and translocation of carbohydrates.
- (4) The combined NPK treatments showed excellent growth synergy, hence the maximum yield.

The micronutrient profile provides the true response of macronutrients, thus forming a reliable basis for improving nutrient management in hydroponic rice systems in controlled environments.

4.4. Nutrient Treatment Design

Table 4 shows the impact of different N-P-K nutrient combinations upon rice yield characteristics with respect to grain weight, straw weight, and tillering number. Each pot (1–29) was assigned a unique nutrient formulation, while calcium (Ca), magnesium (Mg), zinc (Zn), iron (Fe), manganese (Mn), molybdenum (Mo), boron (B), and copper (Cu) were fixed as micronutrients by adding CaCl_2 , MgCl_2 , ZnCl_2 , FeCl_3 , MnSO_4 , $(\text{NH}_4)_2\text{MoO}_4 \cdot 4\text{H}_2\text{O}$, H_3BO_3 , and CuCl_2 , respectively, in constant amounts among all pots, so that differences in plant performance would represent only the varied NPK levels.

Table 5 means growth and yield response of rice plants as influenced by different groupings of nutrient concentration and combination with respect to N, P, and K on the total performance of plants. There is a distinct change between the treatments; thus, nutritional balance has played a major role in regulating physiological vigor, tillering ability, and yield potential.

The N-only group, Pots 1–4, had an average N concentration of 8.5 ppm and gave a moderate type of vegetative growth: leaves were healthy green in color and the canopy developed accordingly. However, grain and straw weights remained considerably low, at 50 g and 25 g, respectively, since phosphorus and potassium, necessary for reproductive growth and energy transfer, were lacking. Plants showed adequate tillering-14 tillers-and a moderately tall height of 27 cm, which showed that ni-

trogen alone causes the leaves and stem to grow but is not sufficient for maximum yield formation.

P-only supplied [Pots 5–8] and K-only supplied [Pots 9–12] treatments gave the worst growth responses among the nutrient-supplied ones. In the case of P-only plants, yield was the lowest (25 g grains, 12 g straw) with a short plant height of 12 cm and showing thin stems with chlorotic leaves due to low nitrogen uptake and inefficient photosynthesis. K-only plants showed limited biomass accumulation with 26 g grain and 13 g straw and inadequate panicle filling, though the stems were a little stronger, indicating that potassium alone gives strength to the stem but cannot sustain overall development without the synergistic action of nitrogen and phosphorus.

The dual-nutrient treatments were clearly advantageous over single-nutrient treatments. For the N-P treatment, Pots 13 to 16 produced better vegetative growth and green leaf area with a moderate grain yield of 30g and a higher tiller number of 9. The N-K treatment, Pots 17 to 20, produced better yield (63 g grains, 31 g straw) with an increased plant height of 28 cm, which denoted the synergistic effect of nitrogen and potassium on increased carbohydrate production, tillering, and panicle. For the P-K treatment, Pots 21 to 24 also produced a satisfactory yield of 60 g grains, 29 g straw, and 17 tillers, hence contributing to adequate root development, although the overall yield is significantly lower compared to the N-K treatment, mainly due to limited growth stimulated by the nitrogen nutrient.

The combined mixture of N-P-K pots 25–28 produced the best growth, with the highest maximum mean grain weight of 93 g, straw weight of 45 g, number of tillers of 25, and plant height of 32 cm. This research explains that proper nutrient contributions result in maximum efficiency, assimilation, and overall growth. The plants receiving such treatment exhibited healthy growth, sturdy stalks, and uniform panicles, which clearly indicates a healthy growth environment for the plants.

In contrast, the control treatment (Pot 29), which had no N, P, and K, had a highly stunted growth with a very minimum number of tillers (2 tillers), as well as a deficiency in leaf color and no grains (0 g). This demon-

strates that the requirement for the addition of macronutrients for rice growth is necessary.

Overall, the importance of the synergistic effect of N, P, and K in attaining high yield and mass accumulation in rice is aptly supported by the data. Notwithstanding, nitrogen regulates plant growth, phosphorus plays a vital role in energy metabolism and root growth, while potassium is involved in the process of improved tolerance to abiotic stresses, as well as indulgence in filling the grains. The obtained results demonstrate that moderate ratios, such as 10.50:5.25:10.50 ppm (Pot 26), are sufficient to supply a balanced mixture of nutrients, thus reflecting the efficiency of expertly managed nutrient ratios in a hydroponic cultivation process.

5. Future Research Directions

Future research could widen the horizon of this research by including various varieties of rice with a set of genetic and physiological traits to test their response to nutrition variation under hydroponic conditions. This would improve the generalizability of results related to nutrition optimization for various varieties of rice.

Future studies would involve the convergence of advanced sensing and automation technologies, like IoT sensing, to enable dynamic monitoring of nutrient cycling, environmental, and plant physiological parameters. The integration of machine learning algorithms may help in developing predictive models for nutrient uptake and growth performance and subsequently enhance system intelligence related to nutritional utilization.

Also recommended are long-term and multi-season tests to determine system robustness, repeatability, and resiliency of the designed hydroponic system against changing environmental parameters. These tests would help determine durability, effects of nutrient accumulation, or interactions of stresses at long-term growth periods.

Furthermore, it is recommended that future studies be conducted to investigate the scalability of the laboratory hydroponic system developed to a greenhouse and semi-commercial scale. The cost-effectiveness and energy efficiency, especially when combined with renewable sources, can be compared to normal methods

of growing rice.

Finally, future work should integrate the results obtained from controlled environment hydroponic systems and the validation experiments on the applicability of optimized nutrient management on rice growth and yield under soil-based rice production systems.

6. Conclusions

This research aimed to design and test an IoT-based hydroponic system for rice plants with 29 varied fertilizer doses in a greenhouse environment. The best way to control temperatures, humidity, pH, and electric conductivity was to automate watering, observation, and data collection. This practice helped in uniform growth, along with optimized use of resources. The result revealed that the optimum macronutrient ratios of N:P:K at 10.50:5.25:10.50 ppm and 14:7:14 ppm brought high growth, increased tiller development, and a maximum yield of 93 g per pot. Nutrient-deficit conditions caused reduced growth, chlorosis, and a decrease in yield; hence, proper nutrient use is necessary for maximum production. Coco peat and rice husks were used as growth supports to aerate roots efficiently, apart from conserving soil moisture. The IoT-based monitoring system enhanced the precision and reactivity of environmental controls. The results indicate that integrating controlled-environment hydroponics with digital monitoring technology is a scalable and sustainable method to enhance nutrient delivery and augment rice production. This technique establishes the foundation for precision agriculture and controlled agricultural research in developing nations. It possesses the capacity for extensive food production when integrated with renewable energy and AI-driven nutrient optimization technologies.

Recommendations

As far as the findings of this research are concerned, hydroponic systems are recommended to be used as standardized experimental platforms for controlled rice nutrient research in laboratory settings as well as greenhouse setups. The proposed system is one that serves as an ideal platform for nutrient isolation to facilitate the production of datasets for precision agriculture re-

search.

It is advised that instead of using narrow-spectrum or single-nutrient studies that fail to explore the complete response pattern of the crop, wider-spectrum designs, such as the 29-treatment design utilized in this study, should be adopted by researchers and institutions to improve the results of nutrient optimization studies.

It is further suggested that the greenhouse-based hydroponic system should also comprise the monitoring of pH levels, electrical conductivity, and temperature, as well as environmental conditions, to ensure the stabilization of the system. Additionally, renewable energy sourcing should also be considered in the system if possible.

Policymakers and research parties in agriculture should invest in and implement research hydroponic systems in controlled environments because they provide important tools in improving nutrient use efficiency, stress tolerance in crops, and sustainable food production. Information gleaned from these research tools can help countries develop fertilizer management and precision agriculture programs.

Finally, the hydroponic technique designed can serve as a prototype for any study in the future concerning different cereal crops. This will promote advancement in controlled environment crop studies and sustainable agricultural technology.

Author Contributions

J.A.O.: writing experimental procedure; W.B.A.: modify the experimental procedure; O.A.O. and W.B.A.: supervise the experiment; J.A.O.: prepare the manuscript first draft; M.O.O.: compile and editing the first draft; E.O.O.: editing the manuscript; M.O.O., E.O.O. and W.B.A.: supervise and coordinate the research. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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