International Journal of Agriculture System
Vol. 14 Issue 1, June 2026
Nationally Accredited Journal Decree No. 177/E/KPT/2024
P-ISSN: 2337-9782, E-ISSN: 2580-6815. **DOI: 10.20956/ijas.v14i1.6690**

Investigation of Water Quality and Lighting in Hydroponic Systems

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How to cite: Ong, T.C., Y.C. Ho., and A.A. Buja. 2026. Investigation of Water Quality and Lighting in Hydroponic Systems. *Int. J. Agr. Syst*. 14(1): 29-38.

ABSTRACT

Hydroponic systems offer numerous benefits, including faster plant growth, higher yields, and efficient water and nutrient use. They are also ideal for urban farming and areas with poor soil quality, as they reduce the need for pesticides and minimize land use. The significance of water quality and lighting in hydroponic systems cannot be overstated, as these factors are crucial for maximizing productivity and ensuring sustainable crop production. Therefore, this study investigated the impact of water quality and lighting on hydroponic systems to optimize plant growth and yield. The initial work examined how variations in the type of water, namely tap water, rainwater, and river water, affect green bean growth. Subsequently, the best kind of water was used in the self-designed and fabricated hydroponic system to investigate the effects of white and purple light by measuring the growth of lettuce plants. Findings revealed a strong correlation between water quality and plant growth, with river water under purple light demonstrating a higher growth mean score of 0.90 cm for lettuce compared to rainwater, possibly due to nutrients and trace minerals sourced from the surrounding environment. This study underscores the importance of water quality and lighting selection in hydroponic systems to ensure maximum productivity. By optimizing these simple parameters, farmers can achieve higher yields and more efficient resource use, contributing to the sustainability of agricultural practices.

Keywords:
Hydroponic; lighting; rainwater; river water; tap water.

1. Introduction

Agriculture plays a crucial role in reducing poverty, increasing income, and improving food security for the 80% of the world's poor living in rural areas, who mainly rely on farming for their livelihoods. Generally, agriculture contributes 4% to the global gross domestic product (GDP) and up to 25% of the GDP in some developing countries, making it essential for economic growth. However, traditional farming faces challenges, including the need for extensive land, which is becoming increasingly scarce due to urbanization and infrastructure development. Farmers also struggle with issues such as weather variability, algae growth, and maintaining efficient farming systems. In urban areas, particularly in apartment complexes, residents face additional difficulties owing to the lack of available land for farming, further complicating food production in these regions (World Bank, 2024).

Hydroponic farming has emerged as a cutting-edge agricultural technique aimed at addressing the limitations of conventional farming, particularly in terms of land scarcity and resource efficiency. Unlike traditional methods, hydroponic systems grow crops without soil, using nutrient-rich water solutions and significantly less water. These systems can be set up in vertically or horizontally stacked layers or integrated into unconventional spaces, such as old warehouses or skyscrapers, making them ideal for urban environments where land is limited. The most advanced hydroponic systems utilize controlled environment agriculture (CEA) technology, allowing farmers to precisely regulate temperature, light, humidity, and other environmental factors. This level of control not only enhances crop yield and quality but also reduces the need for pesticides and herbicides in agriculture. Hydroponic farming offers a sustainable alternative to traditional agriculture, contributing to food security while minimizing environmental impact (Benke & Tomkins, 2021; Al-Kodmany, 2023). Therefore, this effort directly aligns with sustainable development goals (SDG) 2: Zero Hunger with an increase in food production and helps address hunger, especially in densely populated areas where conventional farming is not feasible.

Water quality is a critical control variable in hydroponic systems, as it directly influences plant growth, health, and yield. Maintaining optimal water quality involves regulating pH, nutrient concentration, and dissolved oxygen levels to ensure that plants receive the nutrients necessary for robust growth. Poor water quality can lead to nutrient imbalances, reduced growth, and increased disease susceptibility. Recent studies have explored the effects of different water sources on plant growth in hydroponic systems. Heo et al. (2022) found that water sources significantly affected lettuce growth and chlorophyll content, with tap water, bottled water, and groundwater showing different results. Their main findings showed that lettuce did not grow in water alone without a nutrient solution, and the choice of water source used to prepare the nutrient solution affected lettuce growth and chlorophyll content, but not polyphenol content. The uptake of certain ions, particularly Ca and Zn, by lettuce plants was strongly correlated with the dry weight of the harvested lettuce. Similarly, Al-Isawi et al. (2016) compared river, rain, gully pot, and gray waters for irrigation. A few irrigated chili plants suffered from excess nutrients, which led to a relatively poor harvest. High levels of trace minerals and heavy metals were detected in river water, gully pot effluent, and greywater. They concluded that river water produced the highest yields in chili plants and was an alternative to potable water for irrigating chili plants in a hydroponic system. Patel et al. (2022) reviewed various irrigation sources and suggested that river water and rainwater are preferable for plant growth. Different sources of irrigation water, namely rainwater, river water, canal water, tap water, and groundwater, have varying effects on the growth and development of plants. Rainwater and river water are generally good sources of irrigation, while groundwater can be problematic due to high salinity. Therefore, these studies highlight the importance of water source selection in hydroponic systems and its potential effects on plant development.

Lighting is equally crucial because it drives photosynthesis, the process by which plants convert light into energy. Plants require adequate light to grow and thrive. Artificial lighting can be used to supplement natural light and provide a consistent light source for plant growth. Light-emitting diode (LED) grow lights are a popular choice for hydroponic systems because they are energy-efficient and provide a full spectrum of light. The intensity, spectrum, and duration of light must be carefully controlled to maximize photosynthetic efficiency and promote healthy plant development (Xie et al., 2022). Various studies have compared the effects of different LED light spectra on hydroponic lettuce growth. Shailesh (2019) found that a combination of blue and red LEDs significantly enhanced photosynthetic performance compared to white LEDs, suggesting that these colors are more effective for plant growth. For optimal photosynthetic performance in indoor horticulture, a combination of blue and red LED lights is preferred over other light sources. Meanwhile, Yan et al. (2020) demonstrated that white plus red LEDs resulted in higher leaf and root weights of purple leaf lettuce compared to white LEDs but had no significant effect on green leaf lettuce. In addition, white plus red LEDs were more energy-efficient and resulted in higher fresh weights than red plus blue LEDs for both green and purple leaf lettuces. Interestingly, Talib et al. (2020) reported that red LEDs produced the highest number of leaves and weights in lettuce, with an increase in the total weight of lettuce by 28% compared to blue LED. In their study, white LED resulted in the tallest lettuce plants and the highest chlorophyll content in the leaves, highlighting the varying effectiveness of different light spectra. Lastly, Torres Jr. & Omaye (2022) showed that hydroponic lettuce grown under supplemental LED lighting had significantly higher wet and dry biomass compared to ambient light alone or supplemental High-Pressure Sodium (HPS) lighting. LEDs had the most significant positive effect on the growth of lettuce varieties, outperforming HPS and ambient light due to higher irradiance, illuminance, luminous intensity, and luminous efficacy compared to HPS and ambient light. Their data emphasize the superior performance of LEDs in hydroponic settings.

Despite the increasing popularity of hydroponic systems among urban residents and farmers, a significant knowledge gap persists regarding the optimal water type and lighting conditions required to maximize plant growth and yield. While hydroponics offers a sustainable and efficient alternative to traditional farming practices, this lack of understanding of critical areas hampers its effectiveness and limits its broader adoption. Ensuring proper water quality, including pH balance and nutrient content, along with selecting the appropriate lighting spectrum and intensity, is essential for fostering healthy plant development. Therefore, addressing this knowledge gap is crucial for optimizing hydroponic systems and ensuring their success in diverse environments.

To address these challenges, this project utilizes a self-designed hydroponic system tailored for small-scale farming, with potential applications for small and medium-sized enterprises (SMEs). This study investigated the effects of various lighting options and water types on plant growth. Green beans were used as the initial test crop, focusing on the use of tap, rain, and river water. In the second phase of the study, the growth of lettuce under purple and white LED lights was explored. Owing to time constraints, the research was limited to a two-week growing period, recognizing that mature lettuce typically requires up to 70 days to fully develop. Therefore, the findings should be considered preliminary and indicative of early stage plant responses rather than conclusive evidence of overall crop performance throughout the entire growth cycle.

2. Materials and Methods

2.1 Research Location and Time

This study was conducted at Politeknik Kuching Sarawak, Malaysia. The study was conducted over a period of approximately two months and consisted of two experimental phases: (i) evaluation of different water sources for green bean germination and growth, and (ii) assessment of different LED lighting conditions on lettuce growth using a self-designed hydroponic system.

2.2 Materials and Equipment

The materials used in this study included tap water, rainwater, and river water collected from the Sungai Cina and Matang. Green bean and lettuce seeds were selected as the test plants. Cotton wool and rock wool were used as germination media, and A and B nutrient fertilizers were added to provide the essential macro- and micronutrients required for plant growth. The hydroponic system consisted of a water reservoir, PVC piping, net pots, and water circulation system.

The equipment used included a Total Dissolved Solids (TDS) meter for water quality measurements, a ruler for plant height measurements, plastic containers, seedling trays, and 20 W purple-and-white LED grow lights. The experimental setup and research stages are illustrated in the following subsections.

2.3 Methodology

This study was conducted in two phases. In the first phase, three water sources, namely tap water, rainwater, and river water from Sungai Cina, Matang, were evaluated to determine their suitability for hydroponic cultivation. The water samples were placed in separate labelled containers containing cotton wool as the germination medium. The Total Dissolved Solids (TDS) value of each water sample was measured using a TDS meter, as shown in Figure 1(a). Subsequently, 5 mL of A and B nutrient fertilizers were added to each water sample and mixed thoroughly. The "A" component is rich in macronutrients such as nitrogen, phosphorus, and potassium, which are crucial for plant growth, while the "B" component provides vital micronutrients such as iron, manganese, and zinc, ensuring balanced nutrition and optimal plant health (Kumar & Singh, 2020). Green bean seeds were then placed on cotton wool at approximately 1 cm spacing and allowed to germinate for four days. The heights of the three tallest seedlings were measured using a ruler, as shown in Figure 1(b).

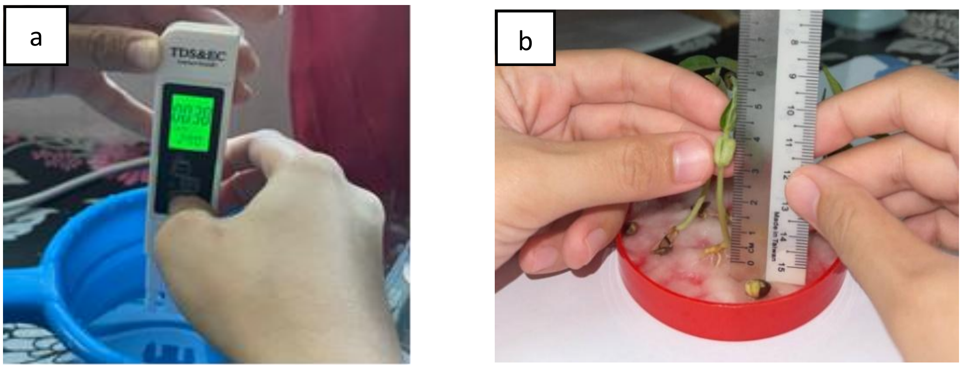

Figure 1. Water source evaluation and green bean germination process: (a) TDS meter used for water quality measurement; (b) measurement of green bean height

Based on the mean height obtained from the green bean experiment, the two best-performing water sources were selected for further investigation using the hydroponic system. Water was poured into the reservoir of the self-designed and built hydroponic system. The development of the hydroponic system (Figure 2(a)) was explained in a previous manuscript (Ong et al. (2024)). Lettuce seedlings were prepared by soaking rock wool cubes in water before placing them in trays, as shown in Figure 2(b). Lettuce seeds were inserted into the center of the rock wool cubes, covered with a cloth, and stored in a dark environment for one day before being exposed to sunlight, as shown in Figure 2(c). Water was added daily to maintain adequate moisture for the growth of the seedlings. After 14 days, the seedlings were ready for transplantation into the hydroponic system (Figure 2 (d)).

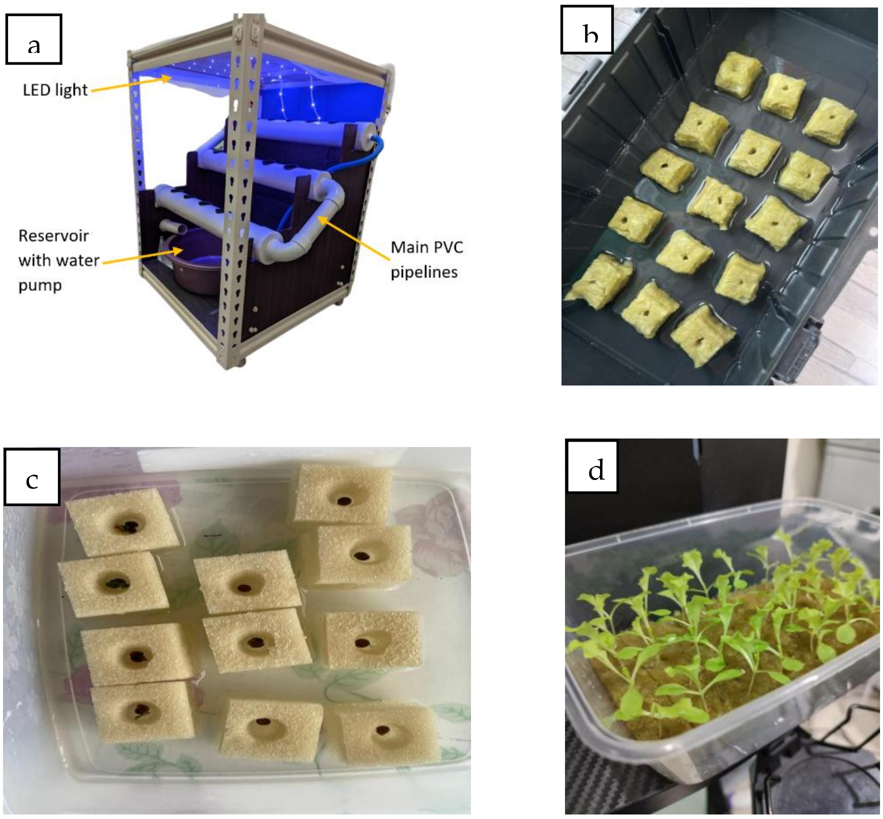

Figure 2. Hydroponic system preparation and lettuce seedling development: (a) completed hydroponic system; (b) preparation of rock wool growing medium; (c) lettuce seed germination in rock wool; (d) 14-day-old lettuce seedlings

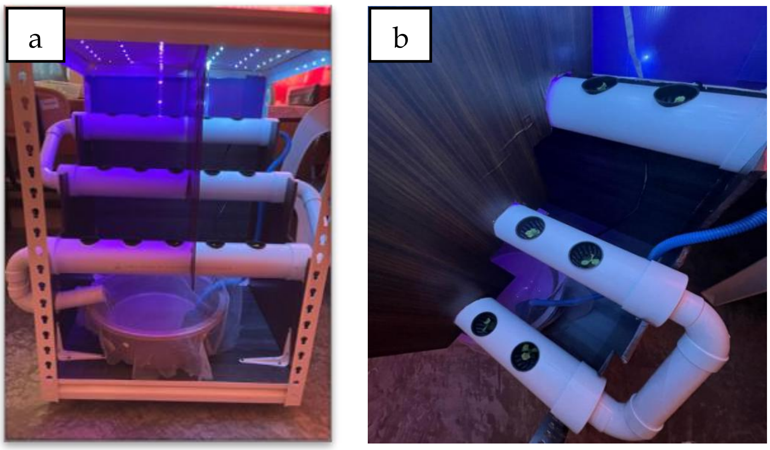

Figure 3. Hydroponic cultivation and lighting treatment: (a) purple and white LED lighting arrangement; (b) lettuce transplanted into the hydroponic system

The second phase focused on evaluating the effects of lighting conditions on lettuce growth. Purple and white LED grow lights were installed above the hydroponic system and separated by a partition wall to prevent light interference between the treatments (Figure 3 (a)). The 20 W LED grow lights were positioned 20 cm above the plant canopy and operated continuously for 24 h per day. The lettuce seedlings were transferred into net pots and placed in a hydroponic system, as shown in Figure 3(b). The nutrient solution consisted of the selected water source mixed with A and B nutrient fertilizers. Plant growth was monitored for 14 days before measurements were performed. The same procedure was repeated using the second-best water source.

2.4 Observation Parameters

Several observation parameters were recorded during the experiment. The TDS of each water source was measured to assess water quality. For the green bean experiment, the heights of the three tallest seedlings after four days of growth were measured and recorded for each treatment. In the lettuce experiment, plant height was used as the primary growth indicator. The heights of the three tallest lettuce plants under each water and lighting treatment were measured after 14 days of cultivation.

2.5 Data Analysis

The collected data were analyzed using descriptive statistics. The heights of the three tallest plants from each treatment were averaged to obtain the mean plant heights. The mean values were compared among the different water sources and lighting conditions to determine the treatment that produced the best growth performance of the fish. The results are presented in tables and graphs to facilitate comparison and discussion.

3. Results and Discussion

Table 1 displays the Total Dissolved Solids (TDS) readings for various water sources, specifically tap water, rainwater, and river water collected from Sungai Cina in Matang. Among these sources, tap water exhibited the highest TDS value, followed by river water, and rainwater recorded the lowest levels. The TDS readings for tap water can vary significantly based on the water source and specific treatment processes employed in Kuching, Sarawak. In less polluted areas, such as Matang, river water TDS levels tend to be lower than those in regions near industrial activities, agricultural runoff, and other pollutants. Conversely, the low TDS reading for rainwater can be attributed to the rural setting of Matang, which is associated with reduced atmospheric contamination.

Table 1. TDS meter readings

Type of water	PPM
Tap water	102
Rainwater	41
River water	79

The observed TDS pattern also suggests that dissolved solids in surface and treated water are influenced not only by source characteristics but also by anthropogenic inputs, such as land use activities and water treatment residues. According to the APHA (2017), variations in TDS are commonly linked to differences in ionic composition and environmental exposure, which can directly affect water suitability for agricultural applications such as hydroponics.

Table 2 presents the initial research findings concerning the growth of green beans. The results indicated that only two types of water were selected for post-testing. River water demonstrated the highest growth value, likely because of its rich mineral content. Rainwater ranks second, exhibiting more consistent growth across the three readings. Conversely, tap water resulted in the lowest average plant height, which could be attributed to the presence of chlorine and other additives in the water treatment process. Consequently, river water and rainwater were chosen for post-testing in earlier research on the development of a hydroponic system, a conclusion that aligns with the findings of Patel et al. (2022).

This selection is also consistent with hydroponic system principles, where water quality directly affects nutrient availability and plant physiological responses. Studies have shown that even minor variations in dissolved ions can influence the germination rate, root elongation, and early biomass accumulation in legumes (Jones, 2004).

Table 2. Initial results

Type of Water	Result 1-R1 (cm)	Result 2-R2 (cm)	Result 3-R3 (cm)	Mean Score (cm) (R1+R2+R3)/3
Tap Water	5.5	5.2	4.5	(5.5+5.2+4.5) /3 = 5.07
River Water	8.5	6.5	7.5	(8.5+6.5+7.5) /3 = 7.5
Rainwater	7.5	7.0	7.5	(7.5+7+7.5)/3 = 7.3

In the subsequent stage of the research, lettuce was cultivated using rock wool and irrigated with both rainwater and river water, each supplemented under distinct white and purple lighting conditions. The three tallest lettuce specimens were meticulously selected and measured using a ruler to determine their height. Figure 4 shows the mean score height measurements across all tested conditions. The growth observations reported in this study primarily reflect early-stage vegetative responses during the initial two weeks of cultivation. Early vegetative growth is often considered an important indicator of nutrient uptake efficiency and photosynthetic performance, which can influence the later developmental stages. Notably, the datum heights of lettuce cultivated in river water were generally lower than those grown in rainwater. The contradictory results observed in earlier studies may be attributed to potential pollution in river water, which could have been exacerbated by continuous rainfall during the collection period. In contrast, rainwater tends to be comparatively cleaner and less contaminated during the heavy precipitation seasons.

The mean growth scores for lettuce irrigated with rainwater under white and purple lights were 0.73 cm and 0.76 cm, respectively. In contrast, the mean growth scores for lettuce grown with river water under the same lighting conditions were 0.83 cm and 0.90 cm, respectively. Interestingly, despite the lower overall heights, the mean growth scores for lettuce irrigated with river water were higher than those associated with rainwater under both lighting conditions. River systems are typically rich in nutrients and minerals sourced from the surrounding landscapes. These essential elements, including nitrogen, phosphorus, potassium, and various trace minerals, are critical for the growth and survival of aquatic organisms such as fish, invertebrates, and plant life. The presence of these minerals can significantly enhance plant growth (Cole et al., 2020). Therefore, as emphasized by Al-Isawi et al. (2016), careful selection of river water, characterized by adequate nutrient content and minimal pollution, can lead to a relatively rich harvest.

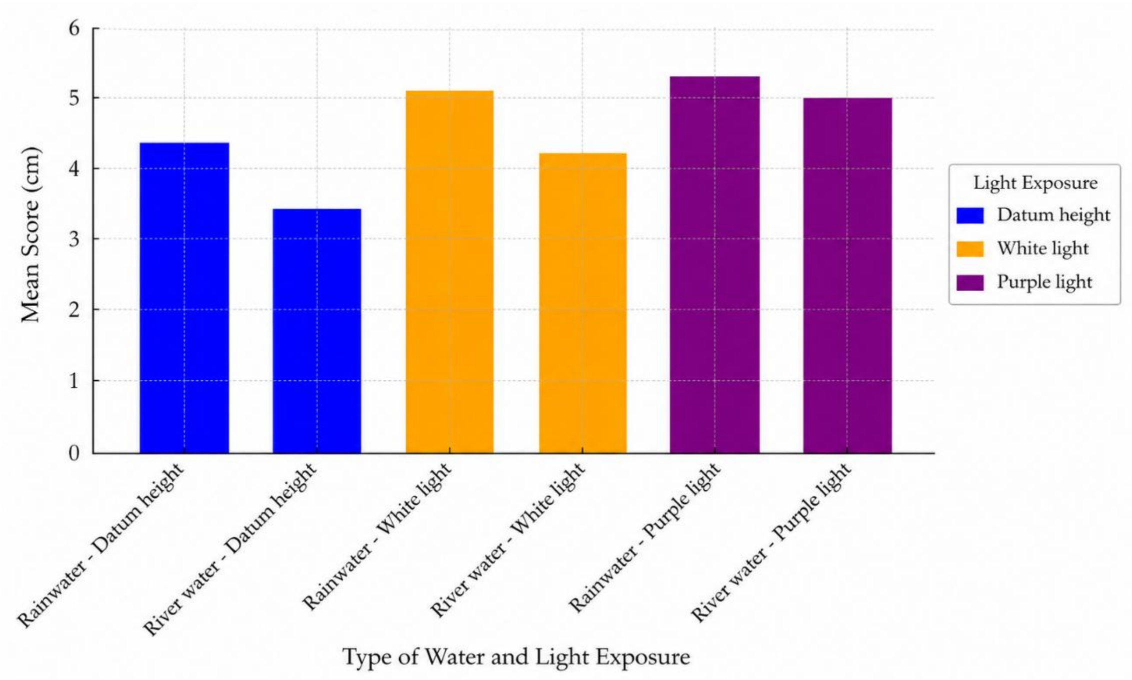

Figure 4. Post-testing results

In terms of lighting, purple light yielded a superior growth rate compared to white light in both waters. This observation aligns with the findings of the literature (Shailesh, 2019), which indicates that purple LED fixtures typically consist of a combination of red and blue LEDs, with red lights accounting for approximately 75–90 percent and blue lights for 10–25%. Red light is recognized as the most effective wavelength for driving photosynthesis; however, many plants exhibit elongated growth under red light alone. The inclusion of blue light promotes compactness, resulting in a more traditionally shaped or shorter plant. The superior performance of purple lighting can be attributed to its provision of the essential light spectrum for plant growth, while maximizing energy efficiency and allowing for customization to optimize development. Although white light can support plant growth to some degree, purple light is preferred in hydroponic systems because of its greater efficiency, ability to elicit specific plant responses, and scope for tailoring the light spectrum to achieve optimal growth conditions.

Additionally, the interaction between the light spectrum and nutrient availability may explain the observed variations in lettuce growth performance. Research indicates that red-blue light combinations enhance chlorophyll synthesis and photosynthetic rate while improving stomatal conductance, which supports better nutrient uptake in hydroponic environments (Cavallaro & Muleo, 2022). This synergistic effect suggests that optimal plant growth is not solely dependent on water quality or lighting independently, but rather on their combined influence within controlled cultivation systems.

4. Conclusion

This study successfully investigated the effects of different water sources and LED lighting conditions on plant growth in hydroponic systems. The results showed that river water produced better growth performance than rainwater, and purple LED lighting promoted greater lettuce growth compared to white LED lighting. These findings demonstrate that both water quality and light spectrum play important roles in the optimization of hydroponic crop production. This study provides useful preliminary insights into small-scale hydroponic farming and highlights the need for further long-term investigations to validate the observed growth trends throughout the entire crop growth cycle.

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