JURNAL UPI

ASEAN Journal of Science and Engineering

AJSE ASEAN Journal of Science and Engineering

Journal homepage: http://ejournal.upi.edu/index.php/AJSE/

How to Improve Hydroponic Leafy Vegetable Plant Productivity by Balancing Nutrient Solution, Total Dissolved Solids (TDS), and pH Completed with Literature Review on Standard Vegetable pH & TDS Requirement to Support Sustainable Development Goals (SDGs)

Senny Luckardi[1,], Agis Abhi Rafdhi[1], Annisa Wulan Sari[1], Hewa Majeed Zangana[2], Eddy Soeryato Soegoto[2]*

[1]Universitas Komputer Indonesia, Bandung, Indonesia
[2]Duhok Polytechnic University, Kurdistan, Iraq
*Correspondence: E-mail: senny@email.unikom.ac.id

ABSTRACT

This study explores how to improve the productivity of hydroponic leafy vegetables by balancing Total Dissolved Solids (TDS) and nutrient solution pH. Using bok choy in a floating raft system, the research applies a controlled experimental design to observe how these parameters interact in supporting vegetative growth and yield. Daily monitoring and careful adjustment of nutrient levels and pH are emphasized to ensure optimal nutrient uptake. Balanced TDS and pH conditions enhanced leaf formation and biomass accumulation, while imbalances caused nutrient stress and growth inhibition. This study offers practical guidance for growers to synchronize TDS and pH in real-time for improved nutrient management. The findings contribute to precision hydroponics aligned with sustainable agriculture, specifically supporting sustainable development goals (SDGs) for SDG 2 (Zero Hunger) through efficient food production and SDG 12 (Responsible Consumption and Production) by encouraging optimal use of agricultural inputs.

ARTICLE INFO

Article History:
Submitted/Received 20 Jun 2025
First Revised 24 Jul 2025
Accepted 03 Sep 2025
First Available online 04 Sep 2025
Publication Date 01 Mar 2026

Keyword:
Hydroponic,
Leafy vegetable,
pH,
Sustainable development goals (SDGs),
Total dissolved solids (TDS).

1. INTRODUCTION

Hydroponics is becoming increasingly popular as a sustainable option to traditional agriculture because of its water and nutrient efficiency. It is also a growth method that allows plants to grow without soil, relying instead on roots that absorb nutrient-rich water solutions. This approach highlights the importance of technology as a key factor in enhancing efficiency and boosting productivity [1]. Bok choy (Brassica rapa var. Chinensis, a widely cultivated leafy green that is grown worldwide, does best with precise management of the nutrient solution for optimal production. Two important factors affecting plant growth in hydroponic systems are Total Dissolved Solids (TDS), which is an indicator of nutrient availability, and pH, which plays a role in how available those nutrients are to the plant roots [2]. However, numerous hydroponic systems continue to depend on individual modifications of these parameters without understanding their possible interaction effects on plant physiology and yield.

Previous studies have shown that when proper TDS levels are achieved, the growth of leafy vegetables like pak choy is greatly enhanced, also within a recommended range in floating raft systems. Extreme fluctuations in TDS have also been linked to osmotic stress, which inhibits root development and nutrient uptake. Similarly, pH plays a vital role in regulating the solubility and absorption of essential nutrients, with stable ranges between 5.8 and 6.2 proving optimal for nutrient availability. While technological advancements have introduced IoT-based systems to automate TDS and pH monitoring, these systems often overlook the physiological implications of TDS-pH interactions on plant growth and productivity [3-6].

This study aims to determine how hydroponic leafy vegetable productivity can be improved by balancing TDS and pH in the nutrient solution. It explores their interaction effects on bok choy growth through systematic monitoring in a controlled floating raft system. By analyzing plant responses such as height, leaf number, and biomass accumulation, the research identifies how synchronized TDS-pH management can support nutrient uptake efficiency. This integrative approach provides practical insights for optimizing nutrient solution control in hydroponics, contributing to precision agriculture and advancing the goals of sustainable food production. Furthermore, the findings are expected to support broader sustainable development goals (SDGs), particularly SDG 2 (Zero Hunger), by improving food production efficiency and responsible consumption and production, which we promote via the efficient and responsible use of agricultural inputs in controlled environment farming.

2. LITERATURE REVIEW

2.1. Concept of Plant Growth in Hydroponic Systems

Plant growth involves a physiological process that is dynamic, complicated, and consists of cell division, cell elongation, and tissue differentiation, all of which require water, certain nutrients, light (radiation), and a stable environment. In most hydroponic systems where plants are grown in a substrate or medium without soil, plant growth depends completely on the controlled delivery of nutrients and water as a nutrient solution. Thus, the nutrient solution's chemical composition and ratio of nutrients become an important factor in achieving successful vegetative growth and yield.

The basic plant needs to support growth consist of macronutrients like nitrogen (N), phosphorus (P), and potassium (K) needed for leaf formation, root development, energy transfer, etc. Micronutrients (or trace elements) include iron (Fe), manganese (Mn), and zinc (Zn), which are also needed, although in smaller amounts, for enzymatic activity and chlorophyll production. In soil-based systems, plants have a natural buffering capacity regarding nutrient regulation, whereas in hydroponic systems, the provision and maintenance of a nutrient solution with correct ionic availability and concentrations is a critical task.

TDS and pH are two primary environmental factors that regulate the availability of nutrients in hydroponics. TDS indicates the total concentration of dissolved ions in the solution and serves as an indicator of nutrient availability in terms of strength or intensity. pH indicates the solubility and chemical form of nutrients and regulates the ability of plant roots to absorb these nutrients. If either of these two factors is imbalanced, it may disrupt nutrient uptake, causing stress responses from the plant such as stunted growth, chlorosis, or reduced photosynthetic efficiency.

Light intensity, temperature, and humidity all contribute more indirectly to modulating plant growth by invoking different metabolic rates through lack of transpirational flow; however, the nutrient solution parameters of hydroponics (specifically, TDS and pH) are the most direct and controllable inputs affecting growth outcomes in controlled-environment agriculture, including hydroponics.

Thus, understanding the physiological needs of plants in a hydroponic environment is critical to interpreting the impact of nutrient solution composition. This study used this foundational knowledge to show how balancing TDS and pH can be leveraged to improve nutrient uptake efficiency, generating improved growth and yield of leafy greens like bok choy.

2.2. Total Dissolved Solids (TDS) in Hydroponic Systems

TDS is a principal measure of nutrient concentration in hydroponic and aeroponic systems [2]. TDS is the sum amount of dissolved salts, minerals, and ions in the nutrient solution and is typically measured in parts per million (ppm). A TDS deviating from acceptable levels on either the lower or higher end will alter uptake and restrict nutrient availability, which will cause inhibited growth or induce physiological stress in plant materials. Therefore, TDS should be monitored and managed to ensure adequate nutrient availability and osmotic balance in the root zone.

As discussed earlier, there is a measurable influence from specific TDS ranges on plant growth. For example, aeroponic spinach was subjected to TDS 1400 ppm at pH 6.0, which resulted in the highest vegetative response. A very similar result has been reported in kale production, with stabilized TDS and controlled temperature contributing to increased yields. TDS at this level (750 ppm) also stimulated Phaseolus vulgaris plant growth, whereas the plant growth from nutrient solutions that had zero TDS did not support any growth at all in plants [3,7,8].

Within the range of edible leafy vegetables, optimum TDS is between 800 and 1400 ppm, and even within this range depends greatly on the species and stage of development. Continuous TDS monitoring, coupled with management of related parameters such as pH and temperature, is essential for maintaining nutrient balance and achieving optimal plant performance.

2.3. The Role of pH in Nutrient Availability

In hydroponic systems, the nutrient availability for plants is defined by the solubility of ions in aqueous solutions and their availability for absorption by plant roots. Many variables influence nutrient solubility, including solution pH, temperature, relative humidity, and interactions among ion groups. Hydroponic nutrient solutions rely heavily on the solubility of nutrients, as compared to soil systems, where natural buffering capacity exists. Because hydroponic solutions lack ion-exchange media, it creates very sensitive to pH deviations from

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2775-6793 e- ISSN 2775-6815

what is regarded as ideal. A pH outside of the recommended range can lead to nutrient precipitation or toxicity, which can disrupt plant metabolism and/or growth.

The pH recommended range for hydroponic solutions is between 5.5 to 6.5. This pH will allow the solubility of the requisite macro- and micro-nutrients to exist in solution, while realizing that nutrient availability can vary at or beyond extreme pH values, such as Fe, Mn, Ca, Mg, and P. At pH values above 7, salt bridges occur in solutions that decrease nutrient availability. In addition, previous studies have noted that acid-based pH adjusters (i.e., phosphoric acid) had greater linear impacts for increased plant growth than organic-based pH adjusters (i.e., vinegar or citrus extracts) for leafy vegetables [9,10].

pH also significantly influences physiological and metabolic processes, including photosynthesis and ion transport. Furthermore, plant species have their own pH specification range, which influences nutrient solution mixing requirements. An optimal pH was 6.0 for Brassica oleracea plants in an NFT system, as deviations above and below 6.0 inhibited growth [9,11].

2.4. TDS and pH Interaction in Plant Physiology

The interplay of TDS and pH is an important factor in soilless cultivation systems (hydroponics and aeroponics) to control nutrient availability, vegetative growth, and overall plant physiological performance. TDS is the measure of the total concentration of dissolved nutrients in the solution, and pH regulates the chemical form and solubility of the nutrients, which affects root uptake.

Several studies have shown the importance of the TDS-pH interactions, noting that at a TDS of 1400 ppm combined with a pH of 6.0 in aeroponic systems, it helped to produce the best growth responses with spinach compared to treatments with either pH or TDS out of the manipulated zone. The authors pointed out that high TDS does not equate to efficient nutrient absorption or vigor if pH is shifted from the optimal range. This highlights the fact that both TDS and pH cannot be optimized in isolation; the uptake of nutrients is reliant upon simultaneous interactions and balance [9].

Low levels of total dissolved solids (TDS) are often indicative of nutrient deficiency and reduced vegetative growth, with experiments conducted with demineralized water (0 ppm) providing no growth to Phaseolus vulgaris. Conversely, very high levels of TDS can cause osmotic stress and discourage water uptake, and will also disturb the uptake percentages of nutrients, and will observable physiological symptoms such as chlorosis, slowed growth rates, and root damage [8]. These two different extremes, low TDS and high TDS, clearly demonstrate a need to have TDS levels within a functional range for supporting physiological equilibrium and plant growth efficiency.

In a similar vein to TDS levels, pH that is either too high or too low adversely affects the bioavailability of nutrients that plants need to function. Higher pH exists by having certain elements like phosphorus and iron, which precipitate and become less available for plant uptake. Conversely, lower pH exists by restricting calcium and magnesium uptake, which is essential for the integrity of cell walls and the photosynthetic process [9,12]. As a result, daily observations of pH are essential in hydroponic nutrient management.

When it comes to the cultivation of bok choy, the desired balance of TDS and pH becomes more precise. Based on the literature values, bok choy grows best at a nutrient solution pH close to neutral (approximately 7.0 pH) and TDS of 1050–1400 ppm. The literature values for bok choy were also confirmed with a larger sample size of leafy vegetables and summarized in **Table 1**, provided as an informative guide for hydroponic growers.

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2776-6098 e- ISSN 2776-5938

This table serves as a physiological baseline, validating the TDS-pH setpoints selected for the experimental design in this study. By aligning the nutrient environment with crop-specific physiological preferences, growers can reduce stress factors and enhance nutrient absorption, leading to improved plant vigor and productivity. Therefore, understanding and managing the interaction between TDS and pH is not only essential for plant nutrition but also offers a clear pathway to improving hydroponic crop outcomes through precision nutrient control.

Table 1. Vegetable pH & TDS requirement summary (https://www.gardeningtita.com/vegetables-ph-tds-ppm-requirements/).

No.	Vegetable	pH	PPM	EC (mS/cm)
1	Ampalaya (Bitter Gourd)	6.4–6.7	1190–1750	2.38–3.5
2	Asparagus	6.0–6.8	1400–2800	2.0–4.0
3	Basil	5.5–6.5	700–1120	1.0–1.6
4	Beans	6.0–6.5	N/A	N/A
5	Broccoli	6.0–6.5	1960–2450	2.8–3.5
6	Cabbage	6.5–7.0	1750–2100	2.5–3.0
7	Capsicum	6.0–7.5	1260–1540	1.8–2.2
8	Cauliflower	6.0–7.0	1050–1400	0.5–2.0
9	Celery	6.0–7.0	1260–1680	1.8–2.4
10	Cucumber	5.8–6.0	1190–1750	1.7–2.5
11	Eggplant	5.5–6.5	1750–2450	2.5–3.5
12	Kangkong	5.5–6.0	600–1200	1.2–2.4
13	Leeks	6.5–7.0	980–1260	1.4–1.8
14	Lettuce	5.5–6.5	560–840	0.8–1.2
15	Melon	5.5–6.0	1400–1750	2.0–2.5
16	Mustasa (Mustard Greens)	5.5–6.5	600–1200	1.2–2.4
17	Okra	6.5	1400–1680	2.0–2.4
18	Onions	6.0–6.7	980–1260	1.4–1.8
19	Pak-choi / Bok-choi	7.0	1050–1400	1.5–2.0
20	Peppers (Bell, Green)	5.8–6.3	1400–2100	2.0–3.0
21	Peppers (Super-hot)	6.0–6.5	2100–2450	3.0–3.5
22	Petchay	5.5–6.5	600–1200	1.2–2.4
23	Pumpkin	5.5–7.5	1260–1680	1.8–2.4
24	Strawberry	5.5–6.0	800–1200	1.6–2.0
25	Tomato	5.5–6.5	1400–3500	2.0–5.0
26	Watermelon	5.8	1050–1680	1.5–2.4
27	Zucchini	5.8	1260–1680	1.8–2.4

3. METHODS

This research used a controlled experimental design to examine how the balance of TDS and nutrient solution pH influences the growth of hydroponic leafy vegetables, focusing on Bok choy (Brassica rapa var. chinensis). The experiment was carried out in a floating raft system within a greenhouse setting, which helped minimize external variables and ensure consistent growing conditions.

Bok choy seedlings were placed in hydroponic containers filled with nutrient solutions that had been prepared at specific TDS and pH levels. These parameters were monitored and

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2775-6793 e- ISSN 2775-6815

adjusted daily using digital TDS meters and pH testers to maintain stability throughout the growth period. In addition, the nutrient solution was replenished as needed to compensate for water loss from evaporation and plant uptake, thereby ensuring continuous treatment conditions.

Growth data were collected regularly to assess how the treatments influenced plant development. Measurements included plant height and the number of leaves, while at harvest, both fresh and dry weights were recorded. Dry weight was obtained by oven-drying the samples at a constant temperature until the mass remained unchanged. The data were then analyzed using descriptive statistics and correlation tests to explore the links between TDS, pH, and plant growth. Graphs and tables were used to present the findings clearly, highlighting how careful management of TDS and pH can improve hydroponic productivity.

4. RESULTS AND DISCUSSION

Figure 1 presents a study of bibliometric analysis that reports on research publications related to hydroponics in terms of its role in improving leafy vegetable productivity via nutrient solution management, TDS, and pH. Detailed information regarding bibliometric analysis is explained elsewhere [13-15]. The data were obtained from the Scopus database using the query "TITLE-ABS-KEY (hydroponics)", with the analysis covering the period from 1937 to 2025.

The search identified 10,568 relevant documents that were published during this time. The distributions towards an enhanced number of publications each year. In the early years (1937 - 1980s), hydroponic research was an underdeveloped field that grew out of the primary stages of hydroponics' effect on vegetable productivity. Slow growth from the 1990's which was then followed by a sharp increase after 2000, which in turn is in response to the worldwide growth in use of modern agricultural technologies and improvement in resource use.

In the last decade, research interest has grown rapidly. In 2017, there were 465 publications, which increased to 702 in 2020, 807 in 2021, and reached 972 in 2023. The highest occurred in 2024 with 1,086 publications, marking substantial attention toward hydroponic systems. Although 2025 shows a decline to 711 documents, the overall trend still indicates strong growth.

The line curve highlights this trend, showing an exponential curve from the early 2000s to 2024. The surge in publications is expected to be influenced by the global urgency to achieve the SDGs, particularly food security (SDG 2), technological innovation (SDG 9), and sustainable production and consumption (SDG 12). Most of the research has focused on improving productivity efficiency through the optimization of pH and TDS levels for various leafy vegetables, while also supporting sustainable agricultural practices.

Overall, the analysis shows that hydroponic research has evolved from a limited field into a prevailing topic in sustainable agricultural innovation. An increasing number of publications underscores the urgency of studying pH and TDS requirements for hydroponic leafy vegetables, eventually contributing to the achievement of the SDGs and the future of a more sustainable global food system.

Following the bibliometric analysis presented in **Figure 1**, which highlights the evolution and increasing research interest in hydroponics over time, the discussion now shifts to a more specific technical aspect, nutrient solution management through the balance of pH and TDS in hydroponic systems. These factors play a crucial role in determining the productivity of leafy vegetables, as imbalances in pH and TDS can directly affect nutrient absorption by

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2776-6098 e- ISSN 2776-5938

plants. Proper management, therefore, offers potential solutions for achieving the SDGs through sustainable agricultural practices.

The plant growth is an essential step in hydroponic cultivation research, as it provides insights regarding plant responses to environmental treatments, particularly nutrient solution pH and TDS. In this study, bok choy (Brassica rapa var. chinensis) was observed periodically to evaluate changes in plant height and leaf number throughout the cultivation cycle. Growth observations are presented graphically to allow visual analysis of vegetative development trends under hydroponic conditions (see **Figure 2**).

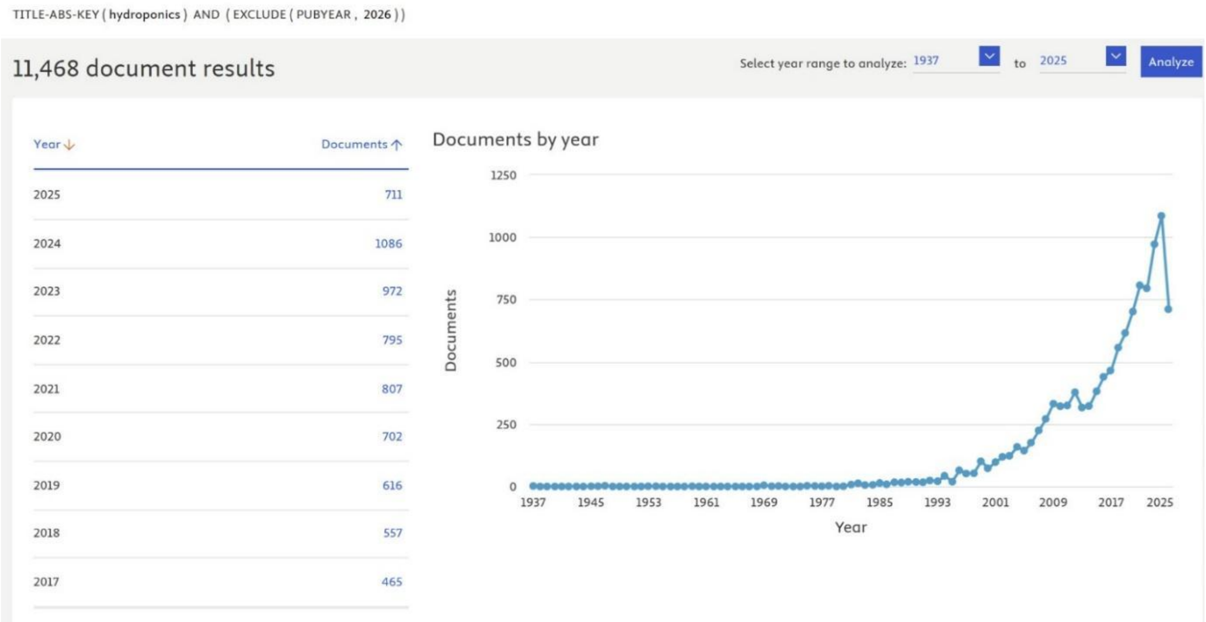

Figure 1. Bibliometric analysis based on the Scopus database using the keyword hydrophonics, taken in September 2025.

Figure 2 shows the progression of bok choy height and leaf count over a 28-day hydroponic growth period. Plant height (blue line) increased gradually from approximately 1 cm on day one to nearly 19 cm by the end of the observation period. During the first 10 days, growth was relatively slow, representing the adaptation phase as seedlings adjusted to the hydroponic medium. From day 11 to day 24, its growth accelerated significantly, indicating an active vegetative phase during which the plants began absorbing nutrients more efficiently to support stem and leaf development. This pattern aligns with previous findings that leafy vegetables in hydroponic systems typically exhibit a growth surge after the initial adaptation stage [12].

The total number of leaves (as shown by the red line) increased from two leaves initially to approximately eleven leaves by the end of the cultivation period. The leaf development progressed steadily throughout the cultivation period with a gradual emergence of new leaves, but the greatest increase in leaves occurred during the midpoint of the study (days 11 to 24), which likely contributed to the production of the leaf canopy that would allow the bok choy to photosynthesise more efficiently. The high degree of leaf production observed in hydroponically-grown bok choy is tightly linked to the acceptable uptake of macronutrients, including nitrogen. These growth patterns suggest that the vegetative phase in bok choy is heavily dependent upon the stability of nutrient availability in solution [16].

As stated earlier in relation to sustainable agriculture, the improved productivity directly bolsters SDG2 (Zero Hunger) because it makes consistent and timely harvests achievable across the limited harvested space of an urban farming system.

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2775-6793 e- ISSN 2775-6815

To further contextualize this growth analysis, it is constructive to also examine the dynamics of their nutrient solution, with a particular focus on the TDS levels (total dissolved solids), which indicate the concentration of dissolved nutrients during the cultivation period for the bok choy. These trends are shown in **Figure 3**.

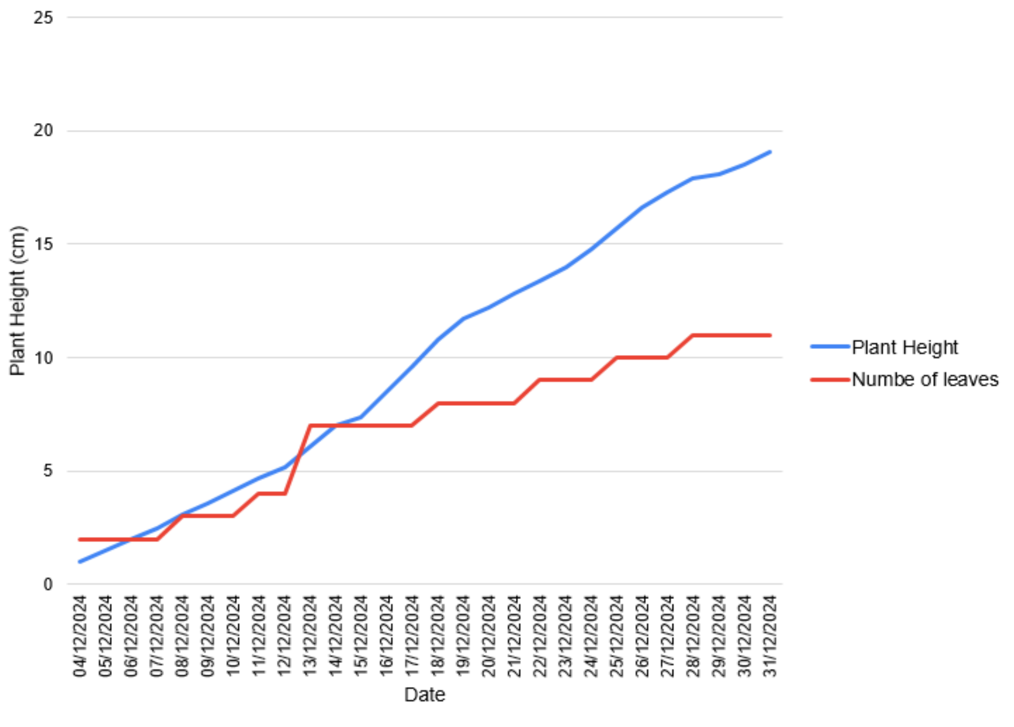

Figure 2. Growth progression of bok choy over 28 days under varying TDS and pH conditions in a hydroponic system.

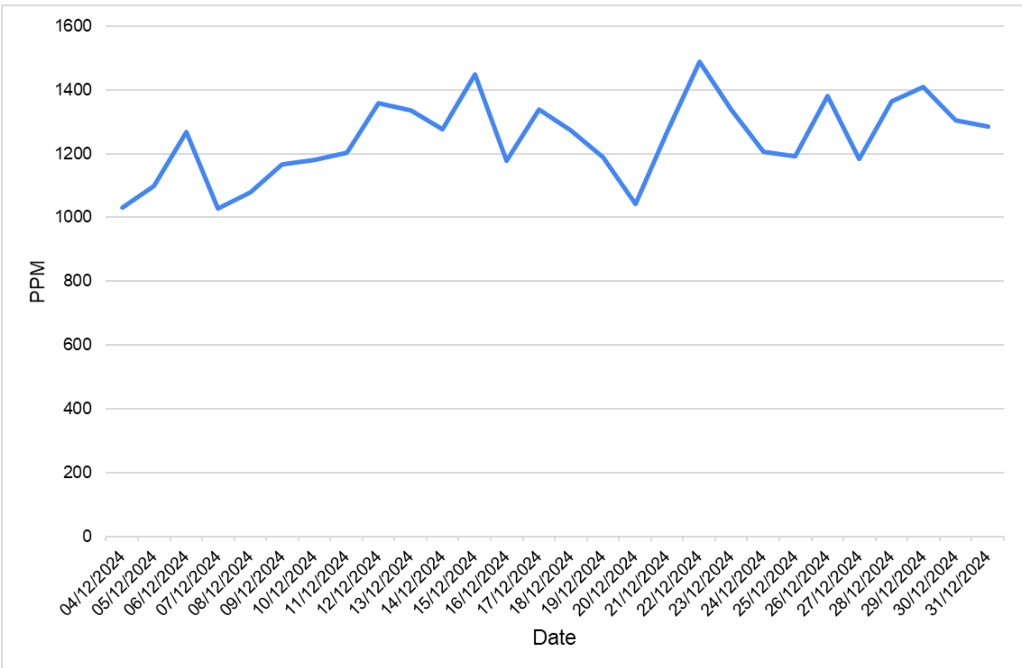

Figure 3. Total dissolved solids data over 28 days.

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2776-6098 e- ISSN 2776-5938

Figure 3 shows fluctuations in TDS values throughout the 28-day observation period. Total Dissolved Solids (TDS) ranged between 1000 and 1500 ppm, which always remained within the recommended TDS range for bok choy (see **Table 1**) of 1050 - 1400 ppm. TDS would increase once concentrated nutrient solutions were added, and then decrease due to plant uptake, evaporative loss, and dilution from the addition of water.

These fluctuations indicate that nutrient management had been adequately done to provide sufficient nutrients over the period in which they were applied.TDS levels remained stable and would have remained in the optimal range, allowing for the uptake of all macronutrients such as nitrogen (N), phosphorus (P), and potassium (K). With TDS falling below the limit, a deficiency resulting in decreased photosynthesis and vegetative growth was entirely possible. On the other hand, if TDS levels remain too high for extended periods of time, osmotic stress may occur by limiting the ability for water uptake, negatively affecting cellular metabolism [3,17].

Precise TDS regulation, as demonstrated in this study, is a key component of smart agriculture and contributes to SDG 12 (Responsible Consumption and Production) by promoting efficient use of inputs such as nutrients and water while minimizing waste.

In addition to TDS, the pH of the nutrient solution plays a vital role in determining the chemical form and solubility of nutrients, which directly influences root uptake. Even minor deviations in pH can render certain nutrients either unavailable or toxic to plants. **Figure 4** illustrates the pH trends observed during the cultivation period.

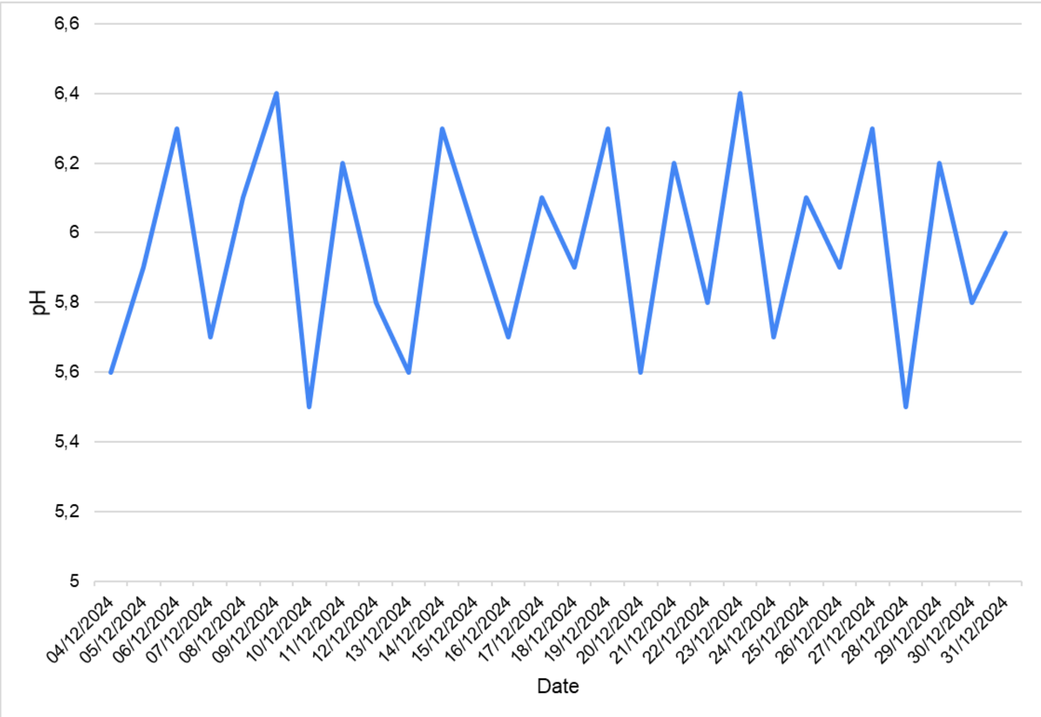

Figure 4. pH data.

As shown in **Figure 4**, the nutrient solution pH fluctuated between 5.5 and 6.4 throughout the experiment. For most of the time, the pH remained within the ideal range of 5.8–6.2, which facilitates the absorption of essential macro- and micronutrients such as phosphorus, calcium, and magnesium [5]. Maintaining pH within this range increases nutrient solubility, thereby supporting leaf development and root expansion.

On several days, pH values approached the lower (5.5) or upper (6.4) thresholds. If left uncorrected, such deviations can reduce the bioavailability of key nutrients. For example,

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2775-6793 e- ISSN 2775-6815

phosphorus and iron tend to precipitate at pH levels above 6.5, while calcium uptake becomes restricted at pH levels below 5.5 [12]. Regular pH monitoring and timely adjustments using acid-based buffers (such as phosphoric acid) are essential for maintaining solution stability [10].

The pH stability also contributes to resource efficiency. Imbalanced pH may necessitate frequent chemical adjustment and reduce the reuse potential of nutrient solutions, thereby increasing both environmental impacts and economic costs. Therefore, effective pH management not only enhances productivity but also aligns with the objective of Sustainable Development Goal SDG 12 by reducing input waste and fostering sustainable resource utilization.

When viewed comprehensively, a strong relationship is evident between the stability of TDS and pH and the growth trajectory of bok choy. The data show that when TDS and pH were maintained within optimal ranges (corresponding to physiological references such as those in Table 1), plant height and leaf number increased more rapidly and consistently. This suggests that nutrients were available in sufficient quantities and in chemically accessible forms, thus supporting photosynthesis, cell division, and tissue expansion [18].

The interplay between TDS and pH exerted a sustainable influence on plant performance up to the harvest stage. Visual assessment of the harvested plants further substantiates the role of nutrient solution management in determining yield outcomes. **Figure 5** displays examples of bok choy plants harvested at the end of the cultivation period.

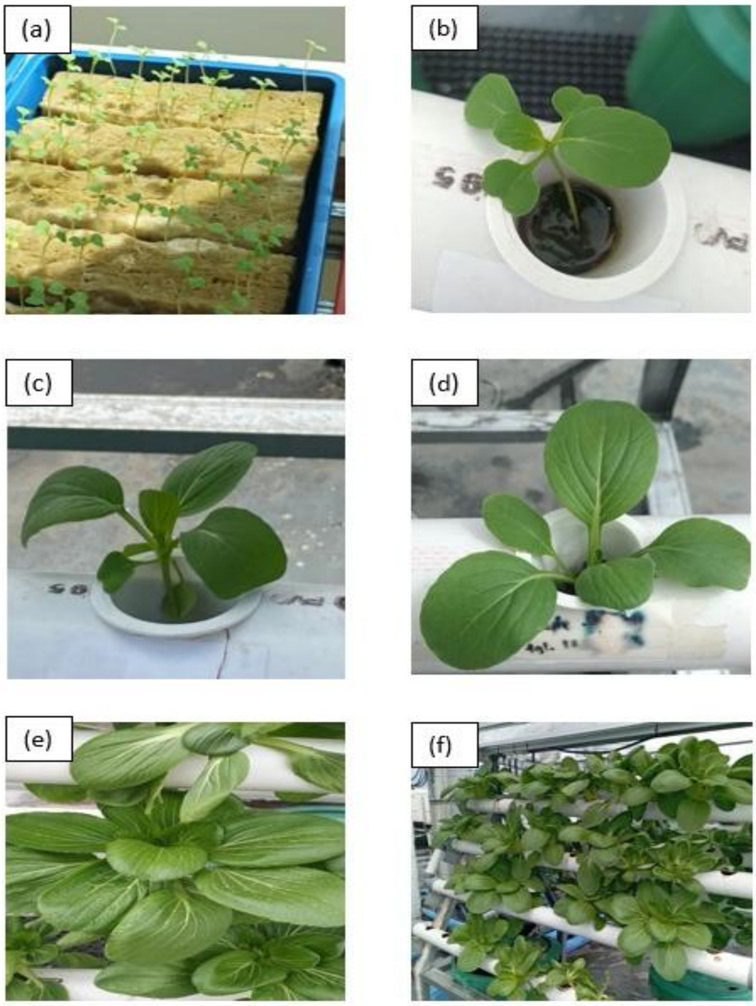

Figure 5. Harvested bok choy plants grown under hydroponic conditions.

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2776-6098 e- ISSN 2776-5938

Figure 5(a) presents bok choy seedlings at approximately three days old during the germination phase, with rockwool serving as the growing medium. At this stage, the seeds have successfully germinated, producing a slender hypocotyl and a pair of cotyledon leaves that function as the initial energy reserves. The emergence of true leaves has not yet appeared, as most of the plant's energy is focused on root development to support the seedling and absorb water and nutrients from the medium. The stems appear thin and fragile, which is typical for this early growth phase. The light green color of the cotyledons indicates that the seedlings are healthy. This three-day stage is a critical period, as the plants are still very sensitive to environmental changes, requiring stable humidity, light, and temperature to ensure proper growth into the next seedling stage.

Figure 5(b) depicts seedlings at approximately seven days old in a hydroponic system. At this stage, the plants have passed the germination phase and entered the early vegetative stage. Morphologically, two cotyledon leaves are still visible, while the first set of true leaves has started to develop with a larger size and a darker green color. The stem appears sturdier compared to the initial stage, indicating that the root system has begun to establish well within the growing medium and can support further growth. The fresh green color of the leaves suggests that the seedlings are healthy and absorbing sufficient nutrients. The seven-day stage is important as it marks the onset of accelerated vegetative growth, during which the number and size of leaves will continue to increase in line with enhanced photosynthetic activity.

Figure 5(c) shows plants at approximately ten days old in a hydroponic system. At this stage, the seedlings have entered a more active early vegetative phase. The true leaves are more developed, with a larger size, an increased number, and a darker green color, indicating that photosynthesis is taking place optimally. The stem appears sturdier to support the expanding leaf structure, while the root system within the growing medium is becoming stronger in absorbing nutrients. The healthy morphology and symmetrical leaf growth suggest that the plants are adapting well to the hydroponic environment. This ten-day stage represents a transition toward faster vegetative growth, where biomass accumulation increases in line with nutrient uptake and photosynthetic activity.

Figure 5(d) shows bok choy plants grown using a hydroponic system. These plants are approximately 14 days old, as indicated by the relatively small size of their leaves, which have begun to form several true leaves in addition to their cotyledons. The leaves appear fresh green, broad, and smooth in texture, indicating healthy growth with adequate nutrient supply. At this stage, bok choy is in the early vegetative stage, where root and leaf development are very important to support further growth until it is ready to be transferred or grown to its maximum growth phase.

Figure 5(e) shows bok choy plants that are approximately 21 days old, grown using a hydroponic system. At this age, bok choy has entered the advanced vegetative growth phase, characterized by an increasing number of leaves, which are wider and densely arranged in a rosette pattern. The leaves appear fresh, green, thick, and healthy, indicating that the plants are receiving sufficient nutrients and light. This is an important stage before entering the maximum growth phase, leading up to harvest, where leaf growth becomes dominant as the part that is consumed.

Figure 5(f) shows bok choy plants that are approximately 28 days old, grown using a hydroponic system. At this age, bok choy has entered its optimal growth phase before harvest. The plants appear to be growing well, with fresh green leaves that are broad and densely arranged to form a compact rosette. The leaves are larger than in the previous phase, indicating that the plants are getting adequate nutrients, light, and water. Similar growth in

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2775-6793 e- ISSN 2775-6815

each planting hole shows that the hydroponic system is working well. At 28 days old, bok choy is usually ready to be harvested or can be left for a few more days to reach the ideal size for consumption.

The interaction between TDS and pH is a key determinant of hydroponic crop performance. This study demonstrates that productivity can be significantly improved by maintaining both parameters within optimal ranges and monitoring them consistently throughout the growing cycle. The findings underscore the importance of synchronizing nutrient concentration and availability in hydroponic solutions, offering growers a clear and actionable strategy for enhancing the yield of leafy vegetables such as bok choy. Beyond practical applications, these insights also contribute to the global agenda of sustainable agriculture and food system resilience, supporting the fulfillment of SDGs 2 and 12. Finally, this study adds new information regarding food science and technology, as reported elsewhere (**Table 2**).

Table 2. Previous studies on food science and technology.

No	Title	Ref.
1	Student development: Implementation of water rocket media as a project-based learning tool to improve the literacy of junior high school students during the pandemic	[19]
2	Factors that affect the performance of selected high school students from the third district of Albay in International Mathematics Competitions	[20]
3	Undergraduate students' awareness of adopting gamification for learning at University of Ilorin, Nigeria	[21]
4	Analysis of teacher skills in e-learning content development during distance learning during the COVID-19 pandemic	[22]
5	Teaching and learning with technology: Effectiveness of ICT integration in schools	[23]
6	Environmental education: A tertiary institution's indoor air quality assessment in Nigeria	[24]
7	Methodology for investigating competency index of technical vocational education and training (TVET) instructors for 4.0 industrial revolution	[25]
8	Improving activities and learning outcomes of elementary school students through experimental methods using lime as an alternative electrical energy source during the COVID-19 pandemic	[26]
9	Community extension: Literacy and numeracy enhancement program for alternative learning system and out-of-school youth learners	[27]
10	Efforts to increase the interest of junior high school students in mathematics lessons using the TikTok learning tool	[28]
11	Literature review: Technical and vocational education and training (TVET) in Malaysia	[29]
12	Education on the importance of food consumed by breastfeeding mothers and exclusive breastfeeding against stunting prevention through PowerPoint media	[30]
13	3D simulation of muscular system in anatomy learning	[31]
14	Development of an animation package in biology for teaching vertebrate, anatomy, and physiology	[32]
15	Learning color theory in elementary school using basic infographic media during the COVID-19 pandemic	[33]
16	Science education research methodology: A case study investigating the correlation between construction, safety, accident, and the effectiveness Construction Industry Development Board (CIDB) Green Card Training Program	[34]
17	Learning of objects, elements, compounds, and mixtures in daily life's elementary school students	[35]

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2776-6098 e- ISSN 2776-5938

Table 2 (continue). Previous studies on food science and technology.

No	Title	Ref.
18	Broensted acids and bases: History, misconception, and application today	[36]
19	Math readiness and its Effect on the online academic performance of science, technology, engineering, and mathematics students	[37]
20	Barriers and measures for enhancing the conduct of transformative research among industrial and technology education lecturers and postgraduate students in university	[38]
21	Effect of conceptual change instructional strategy on chemistry students' performance in acids and bases concepts	[39]
22	Quantitative analysis of the problems and prospects of the Nigerian industrial sector in the 21st century	[40]

5. CONCLUSION

This study confirms that the interaction between TDS and pH in nutrient solutions is a key factor in the growth and yield of hydroponically grown bok choy. Fluctuations in either parameter, especially when outside their physiological optimum, led to observable declines in plant performance. Effects included reduced height, limited leaf development, and lower biomass accumulation. TDS levels that were too low induced nutrient deficiencies. Excessive concentrations caused osmotic stress, which limited water and nutrient absorption. Similarly, pH values outside the range of 5.8–6.2 disrupted the availability of key elements, such as phosphorus, calcium, and iron. This disruption inhibited photosynthesis and vegetative development.

The results indicate that maintaining a precise balance between TDS and pH throughout the crop cycle can significantly increase productivity in hydroponic leafy vegetable cultivation. It is advised to monitor daily and correct imbalances right away. To maximize nutrient uptake and guarantee steady yields, growers can also employ buffering agents or automated control systems. These tactics are both environmentally friendly and technically sound. They increase the usability of nutrient solutions, decrease waste, and encourage effective nutrient use.

This study offers a clear approach to managing chemical balance in hydroponic systems. It contributes to the advancement of sustainable agriculture and the resilience of the food system. The findings align with the objectives of SDG 2 (Zero Hunger) by supporting efficient vegetable production in limited-space environments. The study also supports SDG 12 (Responsible Consumption and Production) by encouraging smarter and more sustainable use of agricultural inputs.

6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

7. REFERENCES

[1] Miftah, H., Alfiah, A., Kusumawati, R., Mubarokah, S. L., Pramartaa, I. Q., Susanti, A. R., and Aidah, Y. (2024). Marketing strategic for hydroponic vegetable product to improve marketing performance base on digital technology. *International Journal of Research and Applied Technology (INJURATECH)*, *4*(1), 193–202.

[2] Alviana, S., Nugraha, R. D., and Kurniawan, B. (2024). Plant nutrition monitoring system for water spinach based on Internet of Things. *International Journal of Informatics, Information System and Computer Engineering (INJIISCOM)*, *5*(2), 146–151.

[3] Catigday, C. J. A., Sace, C., Pascual, C., and Malamug, V. (2023). Relationships of water quality parameters for hydroponic production of kale (*Brassica oleracea*) with in-ground passive cooling system. *CLSU International Journal of Science and Technology, 7*(2), 63–73.

[4] Cho, Y. Y., and Son, J. E. (2005). Effects of planting density on growth and yield of hydroponically-grown Pak-Choi (*Brassica campestris* ssp. *chinensis*). *Journal of the Korean Society for Horticultural Science, 46*(5), 291–294.

[5] Lind, O. P., Hultberg, M., and Bergstrand, K. J. (2020). Biogas digestate in vegetable hydroponic production: pH dynamics and pH management by controlled nitrification. *Waste and Biomass Valorization, 12*(1), 123–133.

[6] Ban, B., Ryu, D., and Lee, M. (2022). Machine learning approach to remove ion interference effect in agricultural nutrient solutions. *Journal of Environmental Control, 17*(5), 24–37.

[7] Huu, D. L., Nhat, H. N. T., and Ngo, X. Q. (2024). Effect of total dissolved solids and pH on the growth and yield of spinach (*Spinacia oleracea* L.) in the aeroponic system. *Academia Journal of Biology, 46*(4), 23–34.

[8] Raj, A., Gupta, A., Gupta, N., and Bhagyawant, S. S. (2023). Effect of water TDS on the growth of plant (*Phaseolus vulgaris*). *International Journal of Plant and Soil Science, 35*(12), 131–136.

[9] Barrow, N. J., and Hartemink, A. E. (2023). The effects of pH on nutrient availability depend on both soils and plants. *Plant and Soil, 487*(1–2), 21–37.

[10] Singh, H., Dunn, B., and Payton, M. (2019). Hydroponic pH modifiers affect plant growth and nutrient content in leafy greens. *Journal of Horticultural Research, 27*(1), 31–36.

[11] Karoba, F., and Nurjasmi, R. (2015). Pengaruh perbedaan pH terhadap pertumbuhan dan hasil tanaman Kailan (*Brassica oleraceae*) sistem hidroponik NFT (Nutrient Film Technique). *Jurnal Ilmiah Respati, 6*(2), 529–534.

[12] Khan, S., Purohit, A., and Vadsaria, N. (2020). Hydroponics: Current and future state of the art in farming. *Journal of Plant Nutrition, 44*(10), 1515–1538.

[13] Rochman, S., Rustaman, N., Ramalis, T. R., Amri, K., Zukmadini, A. Y., Ismail, I., and Putra, A. H. (2024). How bibliometric analysis using VOSviewer based on artificial intelligence data (using ResearchRabbit data): Explore research trends in hydrology content. *ASEAN Journal of Science and Engineering, 4*(2), 251–294.

[14] Al Husaeni, D. F., and Nandiyanto, A. B. D. (2022). Bibliometric using VOSviewer with publish or perish (using Google Scholar data): From step-by-step processing for users to the practical examples in the analysis of digital learning articles in pre and post COVID-19 pandemic. *ASEAN Journal of Science and Engineering, 2*(1), 19–46.

[15] Al Husaeni, D. N., and Al Husaeni, D. F. (2022). How to calculate bibliometric using VOSviewer with Publish or Perish (using Scopus data): Science education keywords. *Indonesian Journal of Educational Research and Technology, 2*(3), 247–274.

[16] Putri, R. E., Fauzia, W., and Cherie, D. (2023). Monitoring and control system development on IoT-based aeroponic growth of Pakcoy (*Brassica rapa* L.). *Jurnal Keteknikan Pertanian, 11*(2), 222–239.

[17] Islam, R., Faysal, S. M., Amin, R., Juliana, F. M., Islam, M. J., Alam, J., and Asaduzzaman, M. (2017). Assessment of pH and total dissolved substances (TDS) in the commercially

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2776-6098 e- ISSN 2776-5938

available bottled drinking water. *IOSR Journal of Nursing and Health Science, 6*(5), 35–40.

[18] Hindersah, R., Maulana, N., Damayani, M., Setiawati, M. R., Suryatmana, P., Fitriatin, B. N., and Setiawan, A. (2023). Effect of biofertilizer with reduced dose of nutrient solution on yield of Pak Choy on Nutrient Film Technique system. *Soilrens, 21*(2), 50–56.

[19] Putra, R. D., and Sakti, A. W. (2022). Student development: Implementation of water rocket media as a project-based learning tool to improve the literacy of junior high school students during the pandemic. *ASEAN Journal for Science Education*, *1*(1), 1-8.

[20] San Jose, M. T. N. (2022). Factors that affect the performance of selected high school students from the third district of Albay in International Mathematics Competitions. *ASEAN Journal for Science Education*, *1*(1), 9-16.

[21] Ekunola, G. T., Babalola, E. O., Omolafe, E. V., and Ibrahim, A. T. (2022). Undergraduate students' awareness to adopt gamification for learning in University of Ilorin, Nigeria. *ASEAN Journal for Science Education*, *1*(1), 17-22.

[22] Nafsi, N. R. R., and Maryanti, R. (2022). Analysis of teacher skills in e-learning content development during distance learning during the covid-19 pandemic. *ASEAN Journal for Science Education*, *1*(1), 23-32.

[23] Jadhav, P., Gaikwad, H., and Patil, K. S. (2022). Teaching and learning with technology: Effectiveness of ICT integration in schools. *ASEAN Journal for Science Education*, *1*(1), 33-40.

[24] Abulude, F. O., Acha, S., Gbotoso, O. A., Arifalo, K. M., Ademilua, S. O., Bello, L. J., and Aladesaye, C. (2022). Environmental education: A tertiary institution's indoor air quality assessment in Nigeria. *ASEAN Journal for Science Education*, *1*(1), 41-48.

[25] Shahroni, N., Minghat, A. D., and Mustakim, S. S. B. (2022). Methodology for investigating competency index of technical vocational education and training (TVET) instructors for 4.0 industrial revolution. *ASEAN Journal for Science Education*, *1*(1), 49-62.

[26] Octaviani, H., Sakti, A. W., and Bilad, M. R. (2022). Improving activities and learning outcomes of elementary school students through experimental methods using lime as an alternative electrical energy source during the covid-19 pandemic. *ASEAN Journal for Science Education*, *1*(2), 63-74.

[27] Arciosa, R. M., Perfecio, J., and Cerado, E. C. (2022). Community extension: Literacy and numeracy enhancement program for alternative learning system and out-of-school youth learners. *ASEAN Journal for Science Education*, *1*(2), 75-80.

[28] Dermawan, R., Muktiarni, M., and Mupita, J. (2022). Efforts to increase the interest of junior high school students in mathematics lessons using the tik tok learning tool. *ASEAN Journal for Science Education*, *1*(2), 81-88.

[29] Minghat, A. D., Mustakim, S. S. B., and Shahroni, N. (2022). Literature review: Technical and vocational education and training (TVET) in Malaysia. *ASEAN Journal for Science Education*, *1*(2), 89-102.

[30] Ibrahim, M. M. M., and Nandiyanto, A. B. D. (2022). Education on the importance of food consumed by breastfeeding mothers and exclusive breastfeeding against stunting prevention through power point media. *ASEAN Journal for Science Education*, *1*(2), 103-112.

[31] binti Shabudin, N. A., bin Zamanhuri, M. A., and Rosli, A. H. (2022). 3D simulation of muscular system in anatomy learning. *ASEAN Journal for Science Education*, *1*(2), 113-116.

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2775-6793 e- ISSN 2775-6815

[32] Ala, N. A., Onojah, A. O., Ishyaku, A. M., and Adamu, S. B. (2022). Development of an animation package in biology for teaching vertebrate, anatomy, and physiology. *ASEAN Journal for Science Education*, *1*(2), 117-130.

[33] Pangestu, T. I., and Sakti, A. W. (2022). Learning color theory in elementary school using basic infographic media during the Covid-19 Pandemic. *ASEAN Journal for Science Education*, *2*(1), 1-6.

[34] Abd Wahab, N., Mahmood, N. H. N., and Minghat, A. D. (2022). Science education research methodology: A case study investigating the correlation between construction, safety, accident, and the effectiveness construction industry development board (CIDB) green card training program. *ASEAN Journal for Science Education*, *2*(1), 7-16.

[35] Zahra, P. R., and Nandiyanto, A. B. D. (2023). Learning of Objects, Elements, Compounds, and Mixtures in Daily Life's Elementary School Students. *ASEAN Journal for Science Education*, *2*(1), 17-22.

[36] Barke, H. D. (2023). Broensted acids and bases: History, misconception, and application today. *ASEAN Journal for Science Education*, *2*(1), 23-32.

[37] Lagcao, Y. G. D., Dechavez, J. P. A. D., Goleng, D. J. G., Lamzon, A. K. E., Tangkli, K. Y. M., and Vicera, W. J. C. (2023). Math readiness and its Effect on the online academic performance of science, technology, engineering, and mathematics students. *ASEAN Journal for Science Education*, *2*(1), 33-38.

[38] Idris, A. M., and Arah, A. S. (2023). Barriers and measures for enhancing the conduct of transformative research among industrial and technology education lecturers and postgraduate students in university. *ASEAN Journal for Science Education*, *2*(1), 39-46.

[39] Swafiyah, B., Muhammad, B. A., and Yamusa, A. Z. (2023). Effect of conceptual change instructional strategy on chemistry students' performance in acids and bases concepts. *ASEAN Journal for Science Education*, *2*(1), 47-54.

[40] Mohammed, S. R. (2023). Quantitative analysis of the problems and prospects of the Nigerian industrial sector in the 21st century. *ASEAN Journal for Science Education*, *2*(1), 55-56.

DOI: https://doi.org/10.17509/ajse.v6i1.89992
p- ISSN 2776-6098 e- ISSN 2776-5938