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Enhancing hydroponic leaf lettuce (*Lactuca sativa*) production through optimized nutrient formulations

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Abstract. *Muttulani MAJ. 2025. Enhancing hydroponic leaf lettuce (*Lactuca sativa*) production through optimized nutrient formulations. Asian J Agric 9: 415-422.* In leaf lettuce production, optimizing nutrient formulations within a hydroponic production system is crucial for enhancing yield, reducing environmental impact, increasing water efficiency, and maintaining a balanced nutrient supply. Despite substantial research, ideal nutrient formulations for lettuce hydroponic production remain insufficiently explored. A well-formulated nutrient solution provides plants with the necessary macro and micro nutrients for healthy growth and development. Thus, this research investigated five nutrient formulations using calcium nitrate, magnesium sulfate, and water-soluble fertilizer on lettuce's growth and yield performance under a hydroponic production system, arranged in a completely randomized design with five replicates. Results revealed that Formulation 3-110 g (NPK) + 70 g $MgSO_4$/ 500 mL H_20 (Solution 1) + 180 g $Ca(NO_3)_2$/500 mL H_20 (Solution 2) significantly improved percentage survival (98%), leaf-sized in terms of its width (16.61 cm) and length (23.64 cm), number of leaves (4.14), heaviest weight of the crown (332.63 g), the longest length of roots (37.20 cm), and highest rooting percentage (98%). The study's findings highlight the significant influence of the aforementioned nutrient formulation on the hydroponic production of lettuce, affecting its quality and yielding an increase of about 60-80%. The study provides a comprehensive insight into optimizing nutrient formulations for loose leaf lettuce production, which can be adapted to other types of lettuce, empowering farmers to significantly increase crop yield, improve food security, increase profitability, and promote sustainable agriculture.

Keywords: Calcium nitrate, lettuce, magnesium sulfate, nutrient formulations, water-soluble fertilizer

Abbreviations: $Ca(NO_3)_2$: Calcium nitrate; $MgSO_4$: Magnesium sulfate; NPK: Nitrogen, Phosphorus, Potassium

INTRODUCTION

In the world, crop cultivation in arable land gradually decreases throughout the year (Lambin 2012). Over the years, due to intensive agricultural production systems, increased salinity and soil productivity depletion have become increasingly evident (Lal 2015; Gomiero 2016). The impact of environmental factors affecting crop production is rising due to the ever-changing climate caused by strong heat, cold waves, and storms (Parry 2019). Moreover, as a result, several crop adaptation practices were used as an alternative crop production system to ensure increasing food productivity and demand. Controlled environmental agriculture, such as a hydroponic system, is one of the sustainable practices that offer a sustainable and innovative approach to food production, reduce environmental impacts, and improve food safety and quality (Gruda and Tanny 2014; Gruda et al. 2019).

The hydroponic production system is a method of growing plants using nutrient-rich water rather than soil. This type of system holds a significant increase in the overall production of crops using minimal resources that utilize water and space (Jones 2016; Chowdhurry et al. 2021). A hydroponic system not only enhances and optimizes crop production but also increases productivity and conserves the use of land and water (Rahman et al. 2018). In this way of production, there is no need for arable land to be cultivated or for the use of land for cultivation. In addition, it also enables considerably less fertilizer application and complete removal or drastic restriction of nutrient leaching in the soil caused by greenhouse gases (Rahman et al. 2017).

The use of recirculating hydroponic nutrient solutions reduces water and nutrient waste (AlShrouf 2017). In determining the nutrient contents in hydroponic solutions, a standard laboratory analysis can be employed; however, time constraints and cost lead hydroponic growers to use simple EC measurement equipment (Richa et al. 2021). Studying nutrient formulations for lettuce production under a hydroponic system is still necessary, even with the existing standard solution, due to variety-specific nutrient requirements, environmental factors, and emerging trends and technologies. Nutrient solution composition may strongly influence microbial activity and plant uptake, with the effects on yield and resource use efficiency (Vandam et al. 2017; Cifuentes-Torres et al. 2020).

In the Philippines, lettuce production is a challenging but rewarding endeavor. This crop became an all-year-grown food, a seasonal vegetable with a wide range of species. Lettuce grown under hydroponic techniques permits sustainable cultivation or harvest within a short duration of time (Nótári and Ferencz 2013). However, under a hydroponic production system, identifying the optimum nutrient solution is a crucial process in plant nutrition, crop yield, and quality, the prevention of nutrient deficiencies, and water quality management. Calcium nitrate, magnesium sulfate, and water-based fertilizers are essential nutrients in hydroponics, playing a critical role in plant growth and development. These elements contain essential functions that include protein biosynthesis, plant metabolism, and act as catalysts and release energy in plants (Nótári and Ferencz 2013). For the optimal nutrient ratios, the ideal nutrients of macronutrients (N, P, K, Ca, Mg) for lettuce are not yet fully understood, leading to potential deficiencies or toxicities. In addition, different crops have unique nutrient requirements, and existing formulations may not cater to these specific needs; for instance, lettuce requires distinct nutrient balances for optimal growth. The hydroponic systems require a dynamic nutrient management, adjusting nutrient levels according to crop growth stages, climate conditions, and plant responses; thus, researchers continue to formulate new nutrient solutions to address these knowledge gaps and improve crop yields, quality, and sustainability (Almeselmani 2022; Brar et al. 2024; Gong et al. 2024)

Therefore, this study aimed to investigate the ideal combination rates of calcium nitrate, magnesium sulfate, and water-soluble-based fertilizer in enhancing the growth yield performance of lettuce under a static closed hydroponic production system. The potential impact of this research could contribute to sustainable agricultural practices, promoting sustainable lettuce production and addressing food security. Moreover, this research could be a potential platform to share relevant information with growers, enthusiasts, and researchers for more efficient utilization of nutrient solution protocols for the production of lettuce under a static closed hydroponic production system. Furthermore, the outcomes of the study would not only improve productivity but also optimize lettuce production, reduce environmental impact, and meet consumer demands for high-quality, nutritious fresh produce.

MATERIALS AND METHODS

Lettuce seeds (Green Rapid Loose-Leaf variety) and other materials used in the experiment were procured from a certified and registered agri-supply local store located at Poblacaion, Kabacan Cotabato, Philippines. The experimental area was conducted at Mut'z Marcos Horticulture Garden, Barangay Kilagasan, Kabacan, Cotabato, Philippines, with an area elevation of 21 m from January to March 2024. The environmental condition of the area was generally a hot, humid, and overcast climate with distinct wet and dry seasons. Temperature typically ranges from 71°F or exceeding 100˚F.

Procedures

Installation of the greenhouse

Modified greenhouses were installed in a 10 m^2 (5 x 5 m in width and length) covered with 50% net shading and a 200-micron greenhouse anti-UV plastic sheet. Individual platforms were installed, ideal for a Kratky hydroponic production system set-up. Hydroponic boxes used in the study had dimensions of 35 x 17 x 7.5 inches with 15 holes. A total of 30 hydroponic boxes were utilized throughout the study.

Experimental layout design and treatments

The study was laid out in a Completely Randomized Design (CRD), with 6 treatments, replicated 5 times. A total of 15 sample plants were used and evaluated per treatment. Different formulations as treatments used in hydroponic system were as follows as shown in Table 1: (T1- Control/ without application, T2- 100 g (NPK)+ 80 g $MgSO_4$/500 mL H_2O (Solution 1) + 180 g $Ca(NO_3)_2$/500 mL H_2O (Solution 2); T3- 110 g (NPK)+ 70 g $MgSO_4$/500 mL H_2O (Solution 1) +180 g $Ca(NO_3)_2$/500 mL H_2O (Solution 2); T4- 120 g (NPK)+ 60 g $MgSO_4$/ 500 mL H_2O (Solution 1) + 180 g $Ca(NO_3)_2$/500 mL H_2O (Solution 2); T5-130 g (NPK)+ 50 g $MgSO_4$/500 mL H_2O (Solution 1) + 180 g $Ca(NO_3)_2$/500 mL H_2O (Solution 2*)*; T6-140 g (NPK)+ 40 g $MgSO_4$/500 mL H_2O (Solution 1) + 180 g $Ca(NO_3)_2$/500 mL H_2O (Solution 2).

Preparation of seedling plugs and water-holding substrate

A total of 450 eight (8) oz styroplastic cups were used in the study; the base of each cup was provided with half-vertical slits about 8 cm in length and 2 cm in width. The plastic cups were sanitized using a 3% hydrogen peroxide solution (diluted in water) and soaked for approximately 1-2 hours before drying. Sterilized coco coir was used as a water-holding substrate for the hydroponic production system, which was sanitized by soaking the substrate material in hydrogen peroxide diluted in water for 12 hours and subjected to air drying for another 6 hours.

Table 1. Nutrient formulations used as treatment in the study in lettuce production under a static closed hydroponic production system

Treatment codes	Treatment formulations
Control	No application (without treatment)
F1	100 g (NPK) + 80 g $MgS0_4$/500 mL H_2O (Solution 1) + 180 g Ca $(NO_3)_2$/500 mL H_2O (Solution 2)
F2	110 g (NPK)+ 70 g $MgSO_4$/ 500 mL H_2O (Solution 1) +180 g Ca $(NO_3)_2$/500 mL H_2O (Solution 2)
F3	120 g (NPK)+ 60 g $MgSO_4$/ 500 mL H_2O (Solution 1) + 180 g Ca $(NO_3)_2$/500 mL H_2O (Solution 2)
F4	130 g (NPK)+ 50 g $MgSO_4$/ 500 mL H_2O (Solution 1) + 180 g Ca $(NO_3)_2$/500 mL H_2O (Solution 2)
F5	140 g (NPK)+ 40 g $MgSO_4$/ 500 mL H_2O (Solution 1) + 180 g Ca $(NO_3)_2$/500 mL H_2O (Solution 2)

Hydroponic system set-up, sowing of seeds, bottom watering, and transplanting of seedlings

The location of the set-up was protected from rain and direct heat from the sunlight. The experimental area was covered in a UV plastic sheet with a 200-micron thickness as protection material to pests, diseases, and physiological disorders (e.g., sun damage) affecting lettuce yield. The growing boxes were arranged according to the layout of the experiment. Seeds were carefully sown in a cell tray filled with sanitized coco coir. The seeds were subjected to a fully covered condition for two days to kickstart the germination process. Two days after germination, the seedlings (Figure 1.A) were immediately subjected to bottom watering for twelve days and transplanted in previously prepared seedling plugs filled with sterilized medium substrates. Transferred seedlings were then subjected again to bottom watering for 7 days (Figure 1.B) before transplanting in static closed hydroponic boxes with 15 perforation holes for growth and yield evaluation. The bottom part of the seedling plugs was submerged in the solution for about ½ inch deep and was regularly checked for potential leaks and troubleshooting. Static closed hydroponics do not employ passive aeration, which doesn't require electricity. The root system was separated into two parts: the lower part immersed in nutrient solutions and water uptake, while the upper part, exposed to the air, was used for aeration.

Mixing of nutrient formulations in static closed boxes

Static closed boxes with dimensions of 35" x17" x7.5" were filled with dechlorinated water with an approximate 25-L capacity per box. Formulated solutions were mixed and added to water with a dilution rate of 2 mL/L for both Solution A and B formulations. Total dissolved solids and pH of the water were also monitored using a TDS (total dissolved solids) and a pH meter for solution concentrate recording. After the mixture, seedling plugs with germinated seedlings were carefully placed in a box with holes for evaluation (Figure 1.C). Lettuce was harvested, and data gathering was done at 45 days after sowing (Figure 1.D).

Data analysis

The data gathered were subjected to appropriate statistical data analysis. The F-test through the Analysis of Variance (ANOVA) was used. Analysis of Variance (ANOVA) was conducted to test the significant differences among treatments being evaluated. Data collected was analyzed using the Statistical Tool for Agricultural Research (STAR) software using version 2.0.1. The level of significance was set at 5%, and significant differences were analyzed using Tukey's post-hoc test. This test enabled a pairwise comparison of treatment means, allowing the results to spot the differences between the treatment groups.

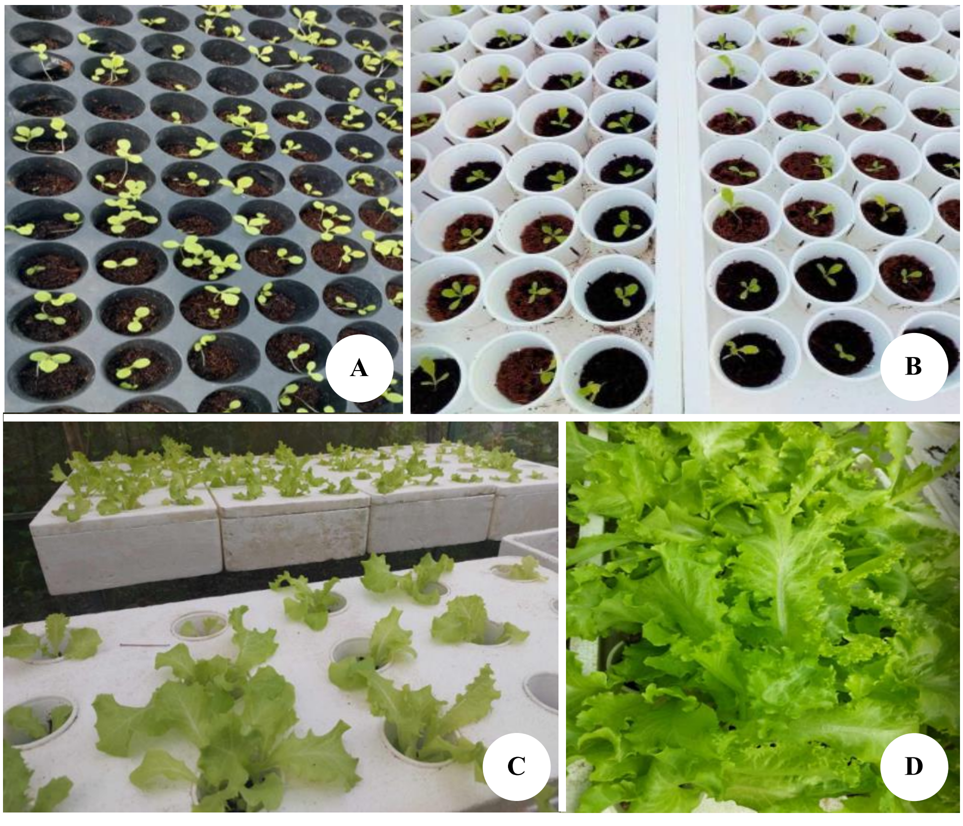

Figure 1. A. Germinated seeds of lettuce 7 days after sowing, B. Bottom watering of lettuce seedlings at 14 days after sowing, C. Lettuce from a hydroponic system 21 days after sowing, D. Harvesting stage of lettuce

RESULTS AND DISCUSSION

Growth and yield parameters of lettuce to different nutrient formulations

Table 2 highlights the significant findings on the percentage survival (%), width of the leaves (cm), length of the leaves (cm), number of leaves and average weight (g) of lettuce 45 days after sowing using different rates of calcium nitrate, magnesium sulfate and water-soluble fertilizer as nutrient formulations under static closed hydroponic production system. The results found that F3 significantly produced the highest percentage survival (98%), the widest width of leaves (161.40 cm), the longest length of leaves (23.64 cm), the largest number of leaves (4.14) and the heaviest weight of crown (332.63 g) of lettuce at 45 days of harvest.

Results were also comparably noted on the width (15.14 cm), length (22.94 cm), and number of leaves (4.22) of lettuce with the use of F4 under a static closed hydroponic production set-up. Moreover, samples without treatment application (control) resulted in the least value in all evaluated data parameters, followed by F1 and F5. Results indicate that the concentration of calcium nitrate, magnesium sulfate, and water-soluble fertilizer (Table 1) influenced the morphological features and quality of harvested lettuce. Optimum concentrations of the abovementioned nutrient solution significantly highlight the effects of nutrient formulation using calcium nitrate, magnesium sulfate, and water-soluble fertilizer on the growth and yield performance of lettuce.

Rooting response of lettuce to different nutrient formulations

Table 3 presents the data on the root length (cm) and rooting percentage (%) of lettuce as influenced by various nutrient formulations using varying rates of calcium nitrate, magnesium sulfate, and water-soluble fertilizer at the harvesting stage. The use of treatment formulations 1, 2, 3, 4, and 5 significantly revealed comparable means, resulting to produced the longest length roots of lettuce harvested at 45 days after sowing (33.00 cm, 33.08 cm, 37.20 cm, 32.20 cm, and 30.80 cm, respectively). On the other hand, the highest rooting percentage (%) was obtained from lettuce grown under Formulation 3, with 98%, which was comparable to lettuce under Formulation 4, with 94%. Moreover, the shortest length of roots and rooting percentage were consistently observed in the treatment control (without application). Indications of the results revealed that the different concentrations of calcium nitrate, magnesium sulfate, and water-soluble fertilizers on the root performance of lettuce significantly influenced the rooting parameters of lettuce under a static closed hydroponic production system.

In summary, among the growth parameters evaluated, the highest percentage of survival was noted on lettuce applied with formulation 3, while the widest and longest length of leaves was obtained from formulations 3 and 4. In terms of the number of leaves, comparable results were observed, where the leaf count ranged from 2.80-4.22, found to be the best using formulations 2, 3, 4, and 5. On the other hand, formulations 2 and 3 obtained the heaviest weight of crown after harvesting the lettuce crop at 45 days after sowing. As to the root parameters evaluated, rooting percentage and root length were generally observed to have great responses with the use of formulation 3. Among the nutrient formulations evaluated, the use of formulation 3-120 g (NPK)+ 60 g $MgSO_4$/500 mL H_2O (Solution 1) + 180 g Ca $(NO_3)_2$/500 mL H_2O (Solution 2) as nutrient solution generally resulted in producing greater yield with an approximate increase of 60-80% in terms of volume of production under hydroponic production system.

Under this type of system, these chemical formulations significantly play a crucial role in promoting healthy root growth and development in lettuce. By providing the necessary nutrients, an ideal concentration of calcium nitrate, magnesium sulfate, and water-soluble fertilizer can support healthy root growth and development in lettuce under a hydroponic production system, ultimately leading to improved crop yields and quality.

Table 2. Data on the percentage survival (%), width of leaves (cm), length of leaves (cm), number of leaves and average weight (g) of lettuce to various nutrient formulations using calcium nitrate, magnesium sulfate and water-soluble fertilizer for a hydroponic production system of lettuce at 45 days after sowing

Treatments	Percentage of survival** (%)	Width of leaves** (cm)	Length of leaves** (cm)	Number of leaves**	Average weight of crown** (g)
Control	48.00^{d}	8.56^{c}	9.60^{d}	2.80^{b}	190.41^{c}
F1	66.00^{c}	13.36^{b}	18.26^{c}	3.68^{a}	302.41^{ab}
F2	78.00^{bc}	13.54^{b}	18.80^{bc}	3.98^{a}	316.60^{a}
F3	98.00^{a}	16.61^{a}	23.64^{a}	4.14^{a}	332.63^{a}
F4	94.00^{ab}	15.43^{a}	22.94^{a}	4.22^{a}	289.00^{ab}
F5	66.00^{c}	13.10^{b}	20.12^{b}	3.94^{a}	249.82^{bc}
F-values	23.87	7.84	24.13	9.62	12.79
C.V. (%)	11.55	4.96	3.84	9.90	11.65

Note: Means followed by different letters superscript are significantly different at $p<0.05$. **: significant

Table 3. Data on the root length (cm) and rooting percentage (%) of lettuce to various nutrient formulations using calcium nitrate, magnesium sulfate, and water-soluble fertilizer for the hydroponic production system of lettuce at 45 days after sowing

Treatments	**Root length (cm) ****	**Rooting percentage (%) ****
Control	12.40^{b}	48.00^{d}
F1	33.00^{a}	66.00^{c}
F2	33.08^{a}	78.00^{bc}
F3	37.20^{a}	98.00^{a}
F4	32.20^{a}	94.00^{ab}
F5	30.80^{a}	66.00^{c}
F-values	25.57	0.46
C.V. (%)	12.90	26.69

Note: Means followed by different letters superscript are significantly different at $p<0.05$, ** significant

Table 4. Correlation coefficient between width and length of leaves (cm) and percentage survival and rooting (%) of lettuce to various nutrient formulations using calcium nitrate, magnesium sulfate and water-soluble fertilizer for hydroponic production system of lettuce at 45 days after sowing

	Width of leaves	**Length of leaves**
Width of leaves	1	
Length of leaves	0.979793477	1
	Percentage survival	**Rooting percentage**
Percentage survival	1	
Rooting percentage	0.923412786	1

Note: The correlation coefficient between the width and length of leaves (0.97) and percentage survival and rooting percentage indicates a very strong positive correlation between the parameters as shown in Table 4. This simply means that in terms of its growth, wider leaves also obtained longer leaves. Moreover, a higher percentage of survival also obtained a higher rooting percentage of lettuce, which is influenced by the application of different nutrient formulations

Discussion

Influence of nutrient formulations ($Ca(NO_3)_2$) on the growth and yield performance of lettuce

The result correlates with the findings of Colonel et al. (2008), who revealed that plants grown under a hydroponic system with ideal nutrient formulation can enhance the chlorophyll content and development of the leaves compared to a conventional soil-based system. This also agreed with a previous study of Sublett et al. (2018), which also suggested that one of the primary factors that influences plant growth and biomass production in hydroponics systems is the use of an ideal nutrient formulation. Moreover, other studies also demonstrated that the lettuce under hydroponic production system significantly response to the nutrient composition essential for producing high-quality lettuce seedlings, for example, Petropeleous et al. (2016), reported that increasing the rate of N from 100 to 200 mg/L increased the plant weight of lettuce by 23.5%-115% (from 12-41.9 kg/m^2) in hydroponic culture. In another related study, Nezamdoost et al. (2022) observed that lettuce plants are sensitive to salinity conditions caused by too much N concentration. Furthermore, situations under high-salinity conditions can cause productivity and physiological disturbances (Ahmed et al. 2019) in addition to less nutrient absorption. The results of these findings inferred that with the excessive level of macronutrient use, such as N, K, and Ca, this could harm plant growth. Similarly, Nurzy´nska-Wierdak (2006) also mentioned that excessive nutrient concentration may reduce the yield and leaf nitrate content of lettuce in a deep-water culture production system and may also bind to the roots, reducing growth (Savvas 2006).

According to Taiz et al. (2017), among the several elements used in hydroponic production systems, calcium nitrate is one of the key factors for plant development structures, in which excessive use or concentration of this element can also contribute to the salinity of water which can potentially harm the plants and disrupt the balance of ions in the solution, affecting plant nutrient uptake. Acosta-Motos et al. (2017), in their study, also revealed that high salinity caused by high concentration of calcium nitrate can cause a reduction in water use efficiency and osmotic potential in plants. Same results were also observed in studies of Khanbabaloo et al. (2018) in tomato, which found that the quality and taste of fruit are influenced by an increase in salinity as well as the glutathione peroxidase (GPX), catalase (CAT), and carotenoid activities; thus, crop yield reduction is inevitable. In the study of Yokoi et al. (2002), they demonstrated that the two roles of calcium in salinity stress are: (i) application of calcium reduces oxidative stress through enzymatic antioxidant activity, and (ii) functions in signaling salinity responses leading to a direct inhibitory effect and adaptation on the Na entry system (Yokoi et al. 2002). With the several findings of the study, there is strong evidence that Calcium nitrate plays a crucial role in hydroponic production due to its nutritional value, impact on plant growth, and stress tolerance.

The use of ideal formulations under a hydroponic production system can optimize plant growth, increase yield, and ultimately lead to more sustainable and profitable production systems. Based on the results of the study, it was found that the F3 obtained significant results among the growth and yield parameters evaluated in lettuce under a static closed hydroponic production system. This indicates that efficient nutrient management can reduce costs associated with nutrient waste and system maintenance. The study demonstrates improved system efficiency when using an ideal concentration of calcium nitrate, magnesium sulfate, and a water-based lettuce fertilizer in a static closed hydroponic production system. Providing essential nutrients in the right proportions supports healthy plant growth and development. This proves that the essential elements have clear physiological processes in plants, and their absence can significantly influence the plant life cycle. Under the hydroponic production system, especially for growing lettuce, it allows greater production and quality of plants year-round (Silva et al. 2015). Based on research findings, the ideal supplementation of this element has been identified to boost calcium levels in lettuce leaves without negatively affecting the biomass. Thus, optimizing calcium nitrate concentrations can lead to higher yields and better-quality lettuce production in hydroponics, with improved appearance and texture.

Influence of nutrient formulations (MgSO4 and water-soluble fertilizers) on the growth and yield performance of lettuce

Results of the study revealed that the optimum concentration of magnesium sulfate and water-soluble fertilizer also enhances the growth and yield performance of lettuce. It is shown that magnesium sulfate and water-soluble fertilizers also play a crucial role in lettuce production, particularly in hydroponic systems. This element is an essential element in chlorophyll development and photosynthetic activity in plant growth, and it also enables plants to resist environmental stress factors such as disease, drought, and heat. According to Malavolta (2006), magnesium is directly related to the synthesis of chlorophyll and photosynthesis as it acts on plant tissues, causing improvements to their visual appearance (greener leaves) and increases in mass deposition. He also revealed that magnesium deficiency resulted in low production of allium species. Similarly, Kleiber et al. (2012) found that in onion, the presence and increased of magnesium nutrition (100 mg/dm^3) resulted in an improved quality and production of onion, which is also observed to have a positive effect, particularly on the dry matter content in leaves, which is a vital parameter in maintaining the quality of onion.

The result of the study correlates with the findings of Souza et al. (2021), which revealed that higher doses of magnesium sulfate contributed to the increased number of leaves, fresh dry mass, and reduced leaf drop in their study in chives. In addition, the extract of chives with the greatest addition of magnesium sulfate (0.48 g/L) in the nutrient solution obtained high pH values, which were replaced by metallic cations, as demonstrated by hydrogen ions. The study also correlated with the findings of Coolong et al. (2004), where they found that the effect of Mg on the accumulation of other nutrients depends on the form of application, plant organ, and species. In his study, the increase in N in chive leaves was observed to have a positive synergistic effect on plant nutrition, on the Mg and N accumulation in the plant.

Similarly, Jiao et al. (2023) also stated that Mg_2+ plays a significant role in transporting carbohydrates from the leaves up to the other developing tissues in plants, which is an essential element in the hydroponic production system. In addition to its metabolic role, this element helps in the maintenance of structural stability in plant cells. Rengel et al. (2015) and Kleczkowski and Iganberdiev (2023) also stated that this nutrient aids in stabilizing cell structures, particularly in nucleic acids, cell membranes, ribosomes, mitochondria, and chloroplasts, ensuring the structural integrity and functional efficiency of plant cells, particularly in hydroponic crop production systems. The application of magnesium in the hydroponic production system is not only influenced by its availability as a nutrient solution but is also important in interactions with other nutrients. Lenz et al. (2013) also highlighted that Mg_{2+} and other elements, particularly calcium, are pivotal for maintaining nutrient homeostasis in plants. This nutrient is an essential component in hydroponic production as a nutrient solution considered one of the macronutrients vital for various physiological processes in lettuce production, including its development, growth, and quality enhancement (Xu et al. 2021; Li et al. 2023c; Tian et al. 2023b). Moreover, research also found that with the identification of the optimum concentration of magnesium in a hydroponic production system, this improved quality harvest influenced the taste, shelf life, texture and nutritional content, thereby driving consumer preferences and market value (Petrescu et al. 2020; Yousaf et al. 2021; Zhang et al. 2021; Mullins and Wolt 2022). In recent years, extensive research has illuminated the complex roles of Mg^{2+}, contributing to a nuanced understanding of its effects on horticultural products (Bashir et al. 2019; Zhang et al. 2020; Quddus et al. 2022).

Compared to the conventional fertilizer application, the nutrient solutions used in hydroponics of vegetable crops can be formulated specifically to meet the nutritional requirements of lettuce, ensuring appropriate proportions of essential nutrients. This has become evident substantially, which has enhanced the quality and yield of lettuce. Consequently, the use of nutrient solutions nowadays is applied in greenhouse agriculture (Stanford et al. 2019). Identification of the optimal range, particularly on the use of water-soluble fertilizer, can raise photosynthesis, chlorophyll content of the leaves, and decrease nitrate levels in lettuce, which improves both the yield and quality of lettuce simultaneously. On the other hand, excessive nutrient solutions can restrict water and nutrient uptake, including the impairment of root activity, which affects the growth and yield performance of lettuce. The water-fertilizer use efficiency and yield of crops are regarded as one of the significant indicators for assessing the quality of water fertilizer (Li et al. 2004).

The biological mechanism and nutrient uptake efficiency of using calcium nitrate, magnesium sulfate, and water-soluble fertilizers as nutrient solutions play a crucial role in the growth performance of lettuce under a hydroponic production system. This study provides practical insights that can be directly applied in the field. As we all know, calcium nitrate promotes healthy plant development, root growth, and cell wall structure that boosts the overall crop yield. On the other hand, magnesium sulfate is a critical component in the production of chlorophyll that is essential in leafy vegetables like lettuce, which helps in protein synthesis and promotes efficient nutrient uptake. At the same time, the use of water-soluble fertilizer provides essential micronutrients and macronutrients supporting overall plant health and development, which is an important component for the successful lettuce production under a hydroponics system. Moreover, environmental conditions, such as EC, pH, dissolved oxygen, and temperature, can also impact nutrient dynamics, plant growth, and nutrient uptake of lettuce under a soilless production system (da Silva et al. 2020; Walter et al. 2020; da Silva et al. 2023).

Studies have shown that the presence of Ca, Mg, and water-soluble fertilizers competes in the capacity of cation exchange, which means that ionic ratios and concentrations had an impact on the elemental composition and nutrient uptake of lettuce leaves (Asaduzzaman and Asao 2019). In this regard, ideal nutrient formulations are important as these ions compete for active sites of the root for absorption; therefore, monitoring the ideal ratios is necessary for a hydroponic production system since it greatly affects the nutrient concentration uptake (Yuanjun et al. 2015; Corrado et al. 2021; Meselmani 2022). Soilless planting conditions nowadays are increasingly used in vegetable production due to their efficient use of resources. Developing effective water and fertilizer management strategies is crucial for promoting sustainable development and achieving high-quality yields. In a study by Zhao et al. (2024), the researchers correlated their findings, which showed that maintaining stable ozone concentrations and using an ideal nutrient solution concentration can initially boost lettuce production under soilless cultivation. In addition, Meskulu et al. (2023) pointed out that the combined application and ideal nutrient chemical formulations used in a hydroponic production system can significantly increase lettuce yield and its constituents, specifically on the maximum plant height, leaf area and increase yield while potentially saving money due to the friendly economic costing of the conventional fertilizer application usage. The optimal use of nutrient levels for hydroponic lettuce production can boost yields, making production more efficient and profitable. Moreover, optimized concentrations can also reduce fertilizer costs, improving profit margin for farmers with sustainable production methods for a competitive edge in the market.

In conclusion, the findings of the study revealed that the ideal nutrient concentration for lettuce production is a mixed formulation of 120 g (NPK)+ 60 g $MgSO_4$/500 mL H_20 (Solution 1) + 180 g Ca $(NO_3)_2$/500 mL H_20 (Solution 2) under a hydroponic production system. This formulation was found to have a great significance for hydroponic leaf lettuce production, impacting its quality, crop yield, and nutritional value. By using this formulation, this could lead to a 60-80% increase in optimal nutrient levels that promote healthy plant growth, higher yields, and efficient nutrient management that minimizes waste and environmental impact. For lettuce producers, the identified nutrient formulation of the study can be recommended as a nutrient solution for leaf lettuce production for high-quality crops, maximizing yields, and promoting sustainable agricultural practices. Furthermore, this can also be used to conduct validation studies in other types of lettuce and other leafy vegetables under a hydroponic production system in both upland and lowland areas using the recommended nutrient formulation under small and large-scale commercial conditions in the tropical Philippines.

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