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Article

Salt industry by-products on lettuce growth and yield in hydroponic culture

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Abstract: Lettuce (*Lactuca sativa* L.) is a nutrient-rich leafy vegetable commonly raw consumed and grown in soilless systems that often rely on expensive chemical fertilizers. Exploring sustainable nutrient alternatives like salt industry by-products (SIB) can reduce input costs and environmental impact. This study aimed to evaluate the effect of SIB as a partial nutrient source on lettuce growth, yield, and nutritional quality in a soilless culture system. The experiment was conducted at the Central Laboratory of Sher-e-Bangla Agricultural University, Dhaka, Bangladesh from September 2014 to March 2015. The base nutrient solution contained NO_3-N (17.05 meqL^{-1}), P (7.86 meqL^{-1}), K (8.94 meqL^{-1}), Ca (9.95 meqL^{-1}), Mg (6.0 meqL^{-1}), S (6.0 meqL^{-1}), and micronutrients Fe (3 ppm), B (0.5 ppm) , Zn (0.1 ppm) , Cu (0.03 ppm), Mo (0.025 ppm), and Mn (1 ppm). Treatments included 0 (control), 0.5 and 0.75 mL^{-1} SIB. The control produced the highest plant height, leaf number, breadth, length, and fresh weight, while 0.75 mL^{-1} SIB-treated plants exhibited the lowest growth but the highest ascorbic acid (157.61 mg/100 g) and beta-carotene (3.21 mg/100 g) contents. The 0.5 mL L^{-1} SIB treatment resulted in moderate yield with balanced nutritional quality, indicating comparable leaf area, relative growth rate, and net assimilation rate to the control. It can therefore be concluded that 0.5 mL L^{-1} SIB may serve as a sustainable nutrient supplement in hydroponic lettuce production. This finding emphasizes the potential of utilizing salt industry by-products as an eco-friendly and cost-effective nutrient source in soilless cultivation systems.

Keywords: transplantation; RGR; soilless culture; nutrient solutions; physiological parameters; ascorbic acid

1. Introduction

Hydroponic cultivation systems have emerged as a promising solution to address global food security challenges, particularly in regions with limited arable land and water resources. Among leafy vegetables, lettuce (*Lactuca sativa L.*) has become one of the most widely cultivated crops in hydroponic systems due to its short growing cycle, high market demand, and adaptability to soilless culture conditions (Sharma *et al*., 2018; Resh, 2022). However, conventional hydroponic production relies heavily on synthetic mineral fertilizers, which pose significant environmental and economic challenges. The manufacturing process of these fertilizers is energy-intensive and contributes substantially to greenhouse gas emissions, while their continuous use raises concerns about resource depletion and environmental sustainability (Bisbis *et al*., 2018). Furthermore, the disposal of spent nutrient solutions from hydroponic systems can lead to water pollution and eutrophication of aquatic ecosystems (Kumar and Chao, 2014).

In response to these challenges, there has been growing interest in developing sustainable alternatives to conventional mineral fertilizers for hydroponic systems. Recent research has demonstrated that various organic waste materials and industrial by-products can serve as effective nutrient sources while simultaneously addressing waste management issues and reducing production costs (Gang *et al*., 2025). Several studies have explored the potential of alternative fertilizers, including poultry biogas slurry, nitrified human urine, aquaponic effluents, food waste-derived liquids, and biofertilizers, with promising results (Monsees *et al*., 2019). For instance, Monsees *et al.* (2019) reported that decoupled aquaponic systems using fish water could reduce greenhouse gas emissions by 72% per hectare while maintaining comparable lettuce yields to conventional hydroponic systems. Similarly, Mauerer *et al.* (2023) demonstrated that nitrified human urine could replace mineral fertilizers without compromising yield, resulting in a 34.25% reduction in carbon footprint and significant savings of nitrogen (48%), phosphorus (13%), and potassium (15%) resources.

The salt industry generates substantial quantities of by-products during the production process, including bittern and other mineral-rich effluents that are often discharged as waste (Wenten *et al*., 2017). These by-products contain various macro- and micronutrients essential for plant growth, such as magnesium, calcium, potassium, and trace elements, making them potentially valuable as liquid fertilizers (Skrzypczak *et al.*, 2021). The utilization of salt industry by-products as alternative fertilizers could provide a dual benefit: reducing industrial waste disposal problems while supplying nutrients for crop production. Preliminary studies in Bangladesh have indicated positive effects of salt industry by-products on hydroponic lettuce growth (Islam *et al.*, 2017), suggesting their potential as sustainable nutrient sources. However, comprehensive investigations into their effects on growth parameters, yield, and produce quality remain limited.

Lettuce production in hydroponic systems is highly dependent on the precise management of nutrient solution composition, electrical conductivity (EC), and pH levels (Trejo-Téllez and Gómez-Merino, 2012). The crop's nutritional requirements include adequate supplies of macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur) and micronutrients (iron, manganese, zinc, copper, boron, and molybdenum) in balanced proportions (Jones, 2016). Alternative fertilizers must meet these nutritional demands while avoiding potential problems such as excessive salinity, nutrient imbalances, or contamination with heavy metals and other toxic compounds (Barbosa *et al*., 2015). Previous research has revealed that some industrial by-products can lead to elevated sodium levels and salinity stress in plants (Mauerer *et al.,* 2023) while others may contain contaminants such as arsenic that exceed food safety limits (Jesse *et al*., 2019). Therefore, thorough evaluation of any alternative fertilizer source is essential to ensure both crop productivity and produce safety.

The evaluation of alternative fertilizers in hydroponic systems typically encompasses multiple parameters, including vegetative growth indicators (fresh and dry weight, leaf number, leaf area, head diameter), physiological responses (chlorophyll content, photosynthetic rate), yield characteristics, and nutritional quality of the harvested produce (Monsees *et al.,* 2019). Wang *et al.* (2019) demonstrated that poultry biogas slurry could replace 50% of mineral fertilizers in hydroponic lettuce production without adverse effects on growth, while also increasing soluble sugar content and reducing nitrate accumulation in leaf tissue. Similarly, biofertilizer applications containing plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) have been shown to enhance lettuce growth parameters and improve nutrient uptake efficiency while reducing mineral fertilizer requirements by up to 50% (Daşgan *et al.*, 2023).

Despite the promising potential of industrial by-products as alternative fertilizers, several research gaps remain to be addressed. First, there is insufficient evidence regarding the standardized composition, optimal application rates, and processing requirements for salt industry by-products in hydroponic systems. Second, the long-term effects of repeated by-product applications on contaminant accumulation in plant tissues and the potential impacts on human health require thorough investigation (Jesse *et al.*, 2019). Third, comprehensive studies comparing the agronomic performance, economic viability, and environmental sustainability of salt industry by-products against conventional mineral fertilizers across different lettuce cultivars and growing conditions are lacking. Finally, the mechanisms by which specific nutrients and bioactive compounds in these by-products influence plant growth, stress tolerance, and produce quality need to be elucidated.

Therefore, this study aims to evaluate the effect of salt industry by-product as an alternative liquid fertilizer on the growth and yield of lettuce in a hydroponic system. Specifically, the objectives are to: assess the impact of different concentrations of salt industry by-product on vegetative growth parameters of lettuce, compare the yield and biomass production of lettuce grown with salt industry by-product versus conventional mineral fertilizer, evaluate the nutritional quality and safety of lettuce produce grown with salt industry by-product, and determine the optimal application rate of salt industry by-product for sustainable hydroponic lettuce production. The findings of this research will contribute to the development of sustainable hydroponic production systems and provide valuable insights into the circular economic approach of converting industrial waste into agricultural resources.

2. Materials and Methods

2.1. Ethical approval

No ethical approval was needed for this research.

2.2. Study area with duration

The experiment was conducted at the Central Laboratory of Sher-e-Bangla Agricultural University (SAU), Dhaka, Bangladesh, from September 2014 to March 2015. Lettuce seeds (cv. Lollo Rossa) were collected from Siddikbazar, Dhaka, Bangladesh (Figure 1). Styrofoam, air pumps, and air stones were procured from Katabon Market, Dhaka, Bangladesh while salt industry by-products (SIB) were collected from Nitaiganj, Narayanganj, Bangladesh (Figure 1). Six white light sources and red plastic sheets were sourced from Boubazar, SAU, Dhaka, Bangladesh (Figure 1). Standard laboratory instruments were used throughout the experiment.

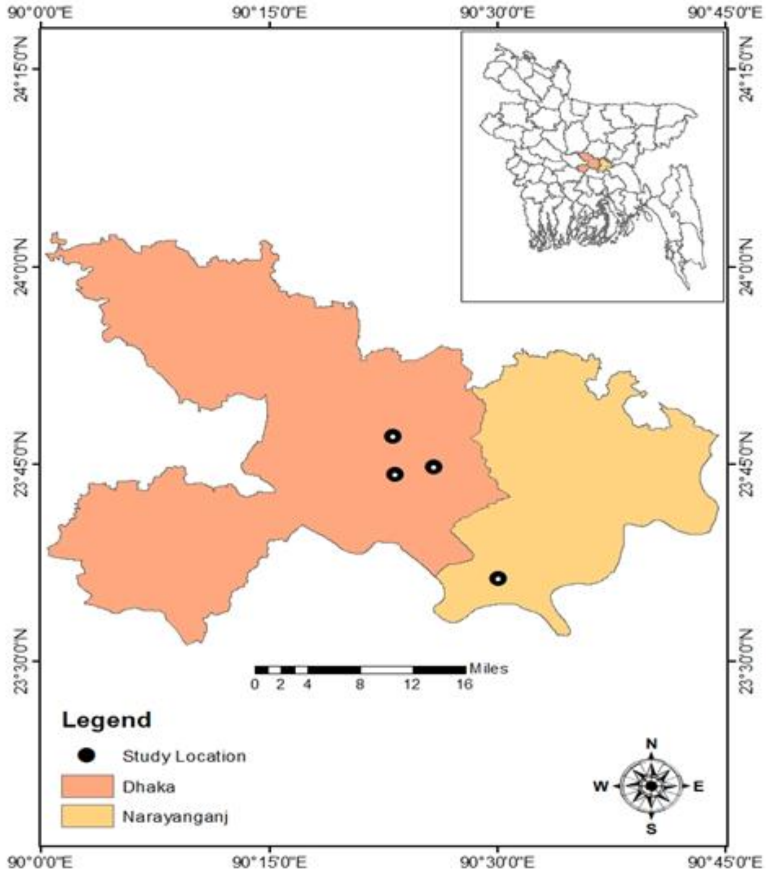

Figure 1. Experimental materials were collected from four different areas of Bangladesh.

2.3. Experimental design

A Completely Randomized Design (CRD) with three replications was used to evaluate the effects of salt industry by-products (SIB) on lettuce growth and nutritional quality in hydroponic culture. Each experimental unit consisted of 15 plants. This study utilized a completely randomized design with three replications to evaluate the effects of different nutrient solutions on lettuce growth. Three treatments were considered such as: Half-strength Rahman and Inden (2012) solution without SIB, plus0.5 mlL^{-1} and 0.75 mlL^{-1} SIB (Table 1).

Nutrient solutions were maintained pH at 6.0. One week after transplanting, a quarter-strength solution was applied; treatments began in the second week. Each treatment was replicated three times.

Table 1. Composition of nutrient solution and SIB concentration.

Treatment	Description	Nutrient solution composition	SIB conc.
T_1 (Control)	Half-strength Rahman and Inden (2012) solution without SIB	NO_3-N (17.05 meq L^{-1}), P (7.86), K (8.94), Ca (9.95), Mg (6.0), S (6.0); micronutrients Fe (3 ppm), B (0.5 ppm), Zn (0.1 ppm), Cu (0.03 ppm), Mo (0.025 ppm), Mn (1 ppm)	0 mL L^{-1}
T_2	Half-strength Rahman and Inden solution with SIB	Same as above	0.5 mL L^{-1}
T_3	Half-strength Rahman and Inden solution with SIB	Same as above	0.75 mL L^{-1}

2.4. Hydroponic culture conditions and transplantation

The experiment was conducted using a non-circulating floating hydroponic system designed with polythene-lined Styrofoam boxes (60 × 40 × 20 cm). Each box was covered with a fitted lid containing 15 plastic cups filled with a 70:30 mixture of coco peat and brick chips (Figure 2). Lettuce seedlings were placed in these cups so that their roots remained directly immersed in the nutrient solution, while continuous aeration was supplied through air stones connected to pumps.

The cultivation took place indoors under controlled lighting, using a combination of red and white artificial lights. Lettuce seeds were soaked and germinated before transplanting, which was performed two weeks after seedling emergence. No weeding or pest management interventions were required during the growth period. The crop was harvested 40 days after sowing.

Key growth and nutritional parameters including plant height, leaf size, fresh weight, dry matter percentage, ascorbic acid content, and β-carotene content were recorded at predetermined intervals throughout the experiment.

Figure 2. Preparation of growing media for seedling development of lettuce.

2.5. Determination of physiological parameters

Leaf area ratio was determined by LAR=$\frac{LA}{PDW}$; Leaf mass ratio was calculated by LMR =$\frac{LDW}{PDW}$; Root weight ratio was as RWR= $\frac{RDW}{PDW}$; relative growth rate was RGR= $\frac{PDW1-PDW0}{(t1-t0)PDW0}$ and net assimilation rate was NAR= $\frac{RGR}{LAR}$

where LAR = Leaf area ratio, LA = Leaf area (cm^2), PDW = Plant dry weight (g), LMR = Leaf mass ratio, LDW = Leaf dry weight (g), RWR = Root weight ratio, RDW = Root dry weight (g) and t = Time. Subscripts 0 and 1 refer to the transplanting and final harvest (days) respectively.

2.6. Statistical analysis of data

Growth parameters (plant height, leaf number, leaf length, leaf breadth, fresh weight, dry weight etc.) and nutritional traits (ascorbic acid, beta-carotene etc.) were recorded at regular intervals. Physiological indices such as leaf area ratio (LAR), relative growth rate (RGR), net assimilation rate (NAR), and leaf mass ratio (LMR) were calculated. Data were analyzed using ANOVA and LSD tests with MSTAT-C software (Version 8.1).

3. Results and Discussion

3.1. Physiological parameters of lettuce

After using salt industries by-products, lettuce plant height exhibited significant changes at 30 DAT (days after transplanting) and 40 DAT (Figure 3). In the present study, control treatment, consisting of half-strength Rahman and Inden (2012) solution without SIB, provided an adequate nutrient supply, leading to greater plant height. These results agree with research by Slamic *et al.* (2016), which found that nutrient solution strength influences lettuce growth. The number of lettuces leaves also exhibited significant differences across treatments such as at 20 DAT, 30 DAT, and 40 DAT (Figure 4). In this study, both control and 0.5 mlL^{-1} SIB treatments provided sufficient nutrients in reachable forms, resulting in a higher number of leaves per plant. Lettuce leaf length is different significantly across treatments throughout the growth period (Figure 5). The highest plant height values were recorded in the control treatment, measuring 5.19, 9.31, 13.21, 15.83, and 17.61 cm at 0, 10, 20, 30, and 40 DAT, respectively. In contrast, the lowest values consistently occurred in 0.75 mlL^{-1} SIB with corresponding lengths of 5.14, 7.80, 10.30, 12.65, and 13.90 cm. These findings support Balansag *et al.* (2023), they demonstrated that lettuce growth is strongly influenced by nutrient mix, particularly when supplemented with salt industry by-products. The present findings are consistent with their results. In this study, control treatment and 0.5 mlL^{-1} SIB treatment supplied nutrients in adequate and available forms, which resulted in greater leaf breadth compared to other treatments (Figure 6).

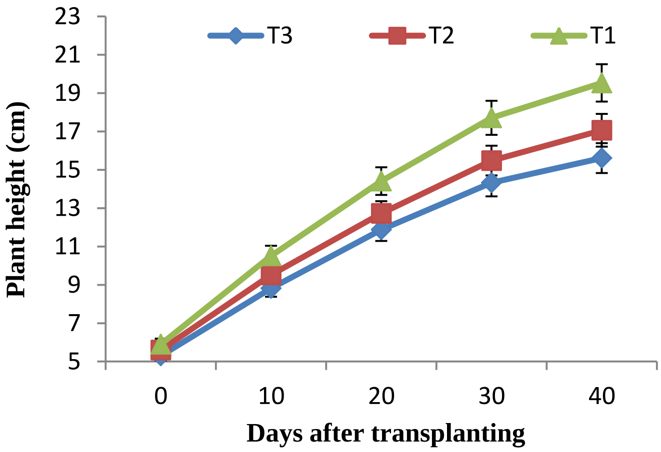

Figure 3. Plant height at different strength of nutrient solutions.

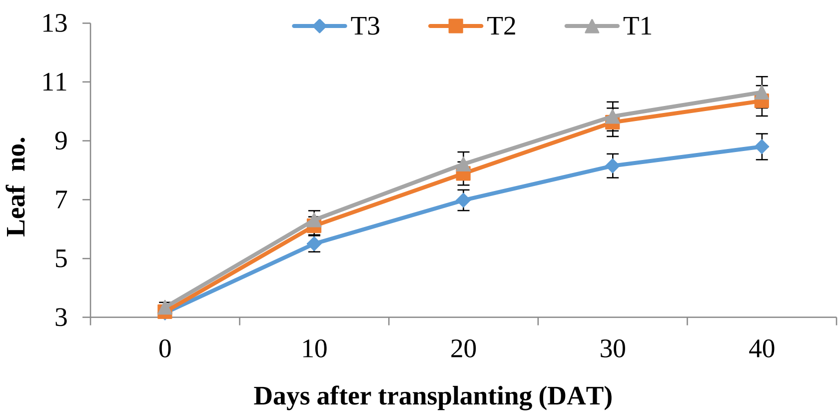

Figure 4. Plant leaf number at different strength of nutrient solutions.

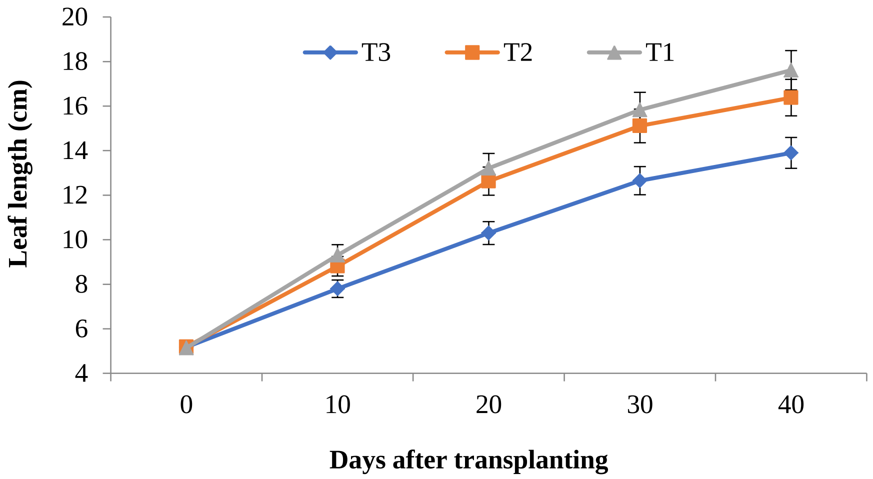

Figure 5. Lettuce leaf length scenario by the application of SIB by control (T_1 treatment), 0.5 ml SIB (T_2 treatment) and 0.75 ml SIB (T_3 treatment).

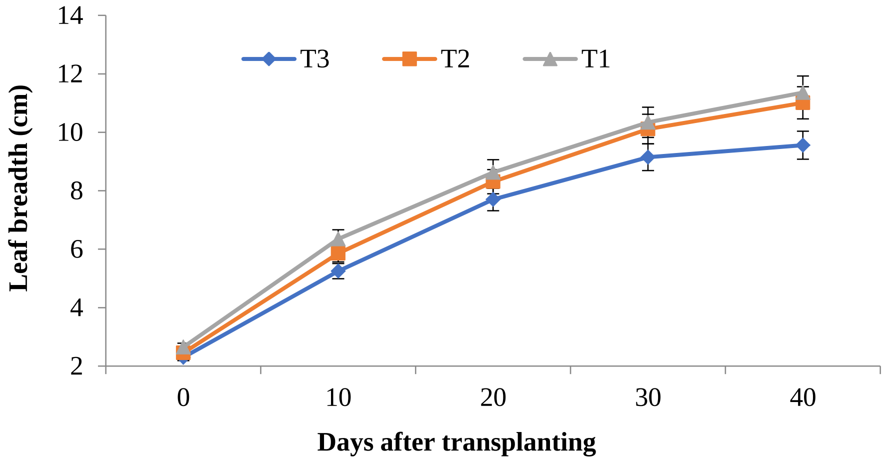

Figure 6. Lettuce leaf breadth scenario by the application of SIB by control (T_1 treatment), 0.5 ml SIB (T_2 treatment) and 0.75 ml SIB (T_3 treatment).

3.2. Fresh and dry weight of lettuce

Marketable quality in lettuce is primarily influenced by plant size, which is closely linked to fresh weight. In this experiment, plants grown under control samples (produced) larger shoots and roots in the closed floating hydroponic system (Figure 7). Significant variation in plant dry weight was also observed across the three treatments (Figure 8). The highest leaf and root dry weights were recorded in the control treatment, showing a similar response to the 0.5 mL L^{-1} SIB application. However, dry weights decreased sharply in plants treated with 0.75 mL L^{-1} SIB.

The nutrient solution of the control treatment contained the highest level of Ca^{2+}**,** a factor that aligned with the superior growth response recorded under this treatment. This observation aligns with previous findings indicating that enhanced calcium supply increases root dry weight and elevates calcium accumulation in plant tissues (Weng *et al.*, 2022).

3.3. Nutrient content of lettuce

The vitamin C (ascorbic acid) content of lettuce differed significantly among treatments. The highest ascorbic acid concentration was recorded in plants treated with 0.75 mL L^{-1} SIB (Figure 9), which also contained elevated levels of Mg^{2+} and K^{+} in the nutrient solution. These ions are known to support the biosynthesis of ascorbic acid, and the present results align with the findings of Ishfaq *et al.* (2022), who reported that higher Mg^{2+} and K^{+} availability enhances ascorbate production and antioxidant activity.

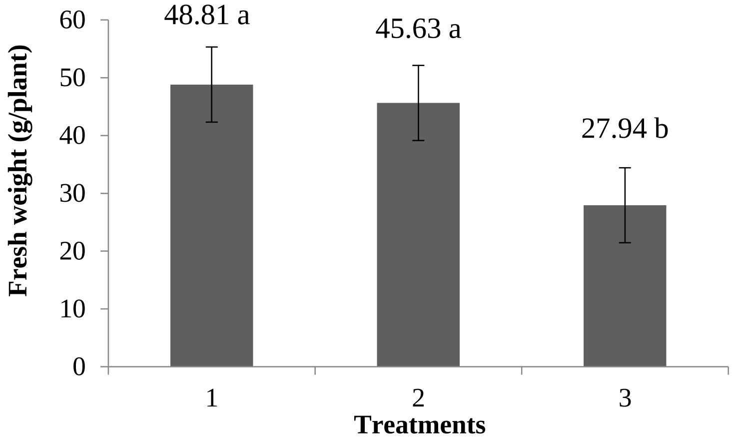

Figure 7. Fresh weight of lettuce plant treated by control (1. T_1 treatment), 0.5 ml SIB (2. T_2 treatment) and 0.75 ml SIB (3. T_3 treatment).

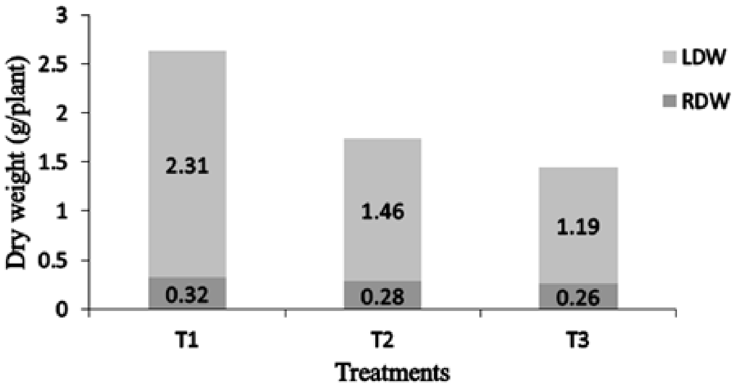

Figure 8. Dry weight of lettuce plant treated by control (T1 treatment), 0.5 ml SIB (T2 treatment) and 0.75 ml SIB (T3 treatment).

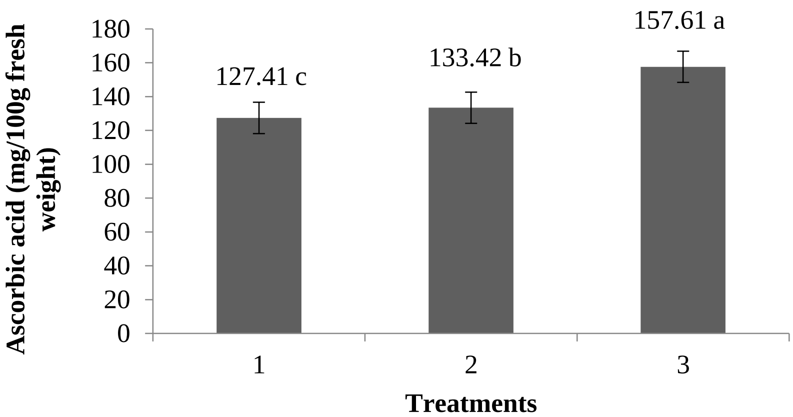

Figure 9. The scenario of lettuce plant ascorbic acid (mg/100g) treated by control (1. T_1 treatment), 0.5 ml SIB (2. T_2 treatment) and 0.75 ml SIB (3.T_3 treatment).

Similarly, the highest β-carotene content was obtained from plants treated with 0.75 mL L^{-1} SIB, followed by 0.5 mL L^{-1} SIB and the control (Figure 10). This indicates that the improved nutrient availability under the 0.75 mL L^{-1} SIB treatment supported greater carotenoid biosynthesis. Comparable results have been reported in hydroponic lettuce, where increased nutrient solution strength promoted carotenoid accumulation, including β-carotene (Miransari *et al.*, 2021).

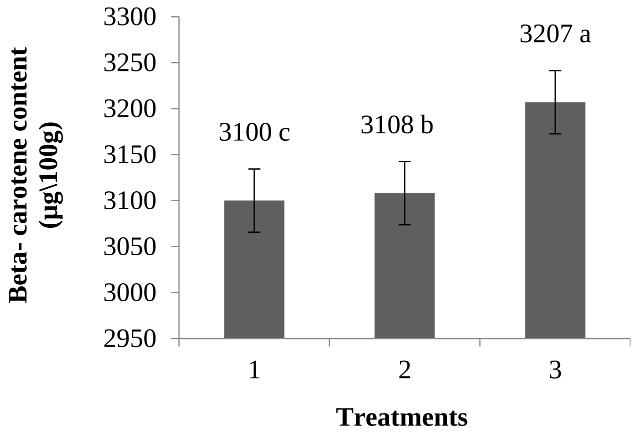

Figure 10. The scenario of lettuce plant beta-carotene (mg/100g) treated by control (1.T_1 treatment), 0.5 ml SIB (2. T_2 treatment) and 0.75 ml SIB (3. T_3 treatment).

Furthermore, increased potassium supply enhances carotenoid and antioxidant accumulation in vegetables (Tavallali *et al.*, 2018), and nutrient-mediated regulation of carotenoid biosynthesis is well established (Saini and Keum, 2018).

3.4. Plant growth analysis

Analysis of combined data from two trials (Table 2) presents that lettuce growth parameters were significantly influenced by the rate of salt industry by-product (SIB) application. Leaf area (LA), leaf mass ratio (LMR), net assimilation rate (NAR), and relative growth rate (RGR) were highest in plants receiving 0 mL L^{-1} SIB, but these parameters decreased markedly at 0.75 mL L^{-1} SIB. Conversely, leaf area ratio (LAR) was lowest in the 0 mL L^{-1} SIB treatment. Similar reductions in leaf area and associated growth indices under elevated salt or nutrient loads have been reported in solanaceous and leafy crops, suggesting that excessive salts or imbalanced nutrient solutions can limit leaf expansion and reduce growth efficiency (Rahman *et al.*, 2017).

Overall, plant growth analysis indicated that 0.5 mL L^{-1} SIB provided the most favorable nutritional conditions among the treatments, enhancing RGR and NAR relative to both the control and the higher SIB level. These findings suggest that moderate SIB application improves physiological performance and growth efficiency in hydroponic lettuce, whereas higher SIB rates may induce osmotic or ionic imbalances that constrain leaf expansion and assimilation (Rahman *et al.*, 2017).

Table 2. Growth behavior of lettuce as affected by salt industry by-product.

Treatment	LA $(cm)^2$	LAR ($cm^2\ g^{-1}$)	LMR ($g\ g^{-1}$)	NAR ($gcm^{-2}\ d^{-1}$)	RWR ($g\ g^{-1}$)	RGR ($g\ g^{-1}$)
T_1	187.4^a	71.27^b	0.88^a	0.00000799^a	0.12^a	0.001^a
T_2	173.1^b	99.48^a	0.84^a	0.00000513^a	0.16^a	0.001^a
T_3	143.2^c	98.75^a	0.82^a	0.00000435^a	0.18^a	0.001^a
P	<0.001	<0.001	>0.05	>0.05	>0.05	>0.05
LS	**	**	NS	NS	NS	NS

*: Significant at 0.05 level of probability; **: Significant at 0.01 level of probability; LS: Level of significance; NS: Not significant; Note: T_1 =Control; T_2 = 0.5 ml SIB and T_3 = 0.75 ml SIB

4. Conclusions

The findings of this study indicate that adding a moderate amount of salt industry by-product improved lettuce growth and enhanced ascorbic acid and beta carotene content in hydroponic cultivation. This suggests its potential as an affordable supplementary fertilizer. However, its long-term impact on nutrient balance and plant health remains unclear. Further research is needed to refine application levels and evaluate commercial suitability.

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Data availability
All data of the study are available in the text and tables of this manuscript.

Conflict of interest
None to declare.

Authors' contribution
Md. Jahedur Rahman designed the study, formulated the experiment, and supervised the experiment; Md. Shariful Islam conducted the research experiment, analyzed data, prepared and wrote the manuscript; Robiul Islam wrote, edited, and corrected the manuscript; Mohammad Zahir Ullah, Prince Biswas, and Md. Golam Ferdous Chowdhury reviewed and corrected the manuscript for final submission. All authors have read and approved the final manuscript.

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