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RESEARCH PAPER

Effect of Nutrient Solution pH on Growth and Yield of Broccoli

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ABSTRACT

In an experiment aimed at optimizing the pH of the nutrient solution for the growth, yield, and quality of broccoli (*Brassica oleracea* var. italica) in a deep water culture hydroponic system (DWC), five pH treatments were included: P_1 = pH level 4, P_2 = pH level 5, P_3 = pH level 6, P_4 = pH level 7, and P_5 = pH level 8. The study took place at Patuakhali Science and Technology University in Bangladesh. Various parameters related to plant growth, yield, and quality were measured during the study. The results revealed that both high (8.0) and low (4.0) pH treatments led to a decrease in broccoli plant biomass, yield, and quality. However, at pH level 6.0 (P_3), the highest values were recorded for leaf area (407.42 cm²), shoot length (28.77 cm), root length (32 cm), curd diameter (14.83 cm), curd fresh weight (242.33 g), and dry weight (28.33 g) at 60 days after transplanting (DAT). The number of leaves per plant, TSS (Total Soluble Solids), total phenols, and titratable acidity content of broccoli curd did not show significant differences among the different pH treatments. The lowest values for leaf area (235.23 cm²), shoot length (19.83 cm), and root length (23 cm) were observed at pH level 8 (P_5). Additionally, the lowest curd diameter (8.83 cm), curd fresh weight (76.67 g), and dry weight (9.80 g) were recorded at 60 days after transplanting (DAT) in treatment P_1 (pH level 4.0). Based on the criteria of broccoli growth and quality, the optimal pH treatment for broccoli in a deep water culture hydroponic production system was found to be pH level 6.0 (P_3). The study concluded that both high and low pH levels limited nutrient uptake, thereby negatively affecting the quality, growth, and yield of broccoli.

Key words: Broccoli, pH, Growth, Yield, Quality

Introduction

Broccoli (*Brassica oleracea* var. italica), a globally recognized vegetable with immature flowers belonging to the Brassicaceae family, holds a significant position in the world of vegetable crops. This is primarily attributed to the abundant evidence of its health-promoting effects, which are linked to bioactive compounds in its edible parts (Raiola *et al*. 2017). Numerous epidemiological studies suggest that vegetables of the Brassicaceae family in general, and broccoli specifically, have the potential to contribute to the prevention of degenerative diseases and certain types of cancer. This potential arises from their richness in glucosinolates and natural dietary antioxidants, including vitamins, flavonoids, and hydroxycinnamic acids (Higdon *et al*. 2007; Moreno *et al*. 2006).

Hydroponic systems facilitate plant growth without the need for soil by utilizing a water and nutrient solution mixture. These systems offer numerous benefits, including enhanced control over plant nutrition, more efficient space utilization, reduced reliance on herbicides and pesticides, and savings in water and fertilizer. Additionally, hydroponics provides precise management of growth conditions, including lighting, humidity, and temperature, which accelerates the growth cycle and boosts yields, all independent of weather conditions. This is especially valuable in situations where arable land is limited or unavailable (Khater *et al*. 2021; Massa *et al*. 2020; Maucieri *et al*. 2019; Sambo *et al*. 2019).

Maintaining the pH of the nutrient solution in an adequate value is crucial for proper crop development because it is directly related to nutrient availability to the plants (Spinu *et al*. 1998). Managing the pH of the nutrient solution represents a significant challenge in soilless cultivation systems. This is because it not only impacts plant growth but also plays a role in influencing various aspects, including dry matter production, as well as the pH levels in the root rhizosphere and apoplast (Putra *et al*. 2015; Marschner, 2011). Limited information is available for broccoli. Typically, the ideal pH range in the root zone for most hydroponically grown crops falls between 5.5 and 6.5 (Sing *et al*. 2019). When the pH in the rhizosphere drops too low levels, it imposes abiotic stress on plants, leading to direct consequences, such as root injury due to high H^+ levels, and indirect effects like limited phosphorus availability, which ultimately hinder plant growth and crop yields (Alam *et al*. 1999). As the pH level increases, the availability of essential nutrients like potassium (K), phosphorus (P), calcium (Ca), and magnesium (Mg) experiences a mild reduction. However, the availability of micronutrients, including manganese (Mn), zinc (Zn), copper (Cu), and most notably, iron (Fe), undergoes a more pronounced decrease (Bugbee 2004). A significant concern arises in the form of leaf chlorosis caused by alkalinity, which results from the deficiency of iron (Fe) due to its diminished uptake and reduced availability (Nikolic & Pavlovic 2018). Of note, broccoli is known for its suitability in hydroponic cultivation, often proving easier to grow within this method compared to other Brassica species (Mason, 2005). Nevertheless, the optimization of pH for broccoli production in hydroponic systems remains an understudied area.

The primary objective of our current investigation was to assess how varying nutrient solution pH levels affect the growth, yield, and quality of broccoli when utilizing a deep water culture hydroponic system. To explore the potential for commercial cultivation of this species, we examined a wide pH range in the nutrient solution, spanning from 4.0 to 8.0.

Materials and Methods

The experiment was conducted at the Germplasm Center of the Department of Horticulture, Patuakhali Science and Technology University (PSTU), Dumki, Patuakhali, Bangladesh. In this study, broccoli (F_1 hybrid of Japani green broccoli) was used as planting materials. The planting materials were purchased from Siddique Bazar, Dhaka, Bangladesh. The experiment consisted of 5 pH levels: P_1 = pH level 4, P_2 = pH level 5, P_3 = pH level 6, P_4 = pH level 7, P_5 = pH level 8. The treatments were based on Cooper's (1979) hydroponic nutrients solution. The nutrient solution consisted of the nutrients concentration of 200 mgL^{-1} N, 60 mgL^{-1} P, 300 mgL^{-1} K, 170 mgL^{-1} Ca, 50 mgL^{-1} Mg, 68 mgL^{-1} S, 1 mgL^{-1} Fe, 0.1 mgL^{-1} Cu, 0.1 mgL^{-1} Zn, 2 mgL^{-1} Mn, 0.3 mgL^{-1} B, and 0.2 mgL^{-1} Mo. The experiment was conducted in the Deep Water Culture (DWC) hydroponic production system. The experimental units were distributed according to a Completely Randomized Design (CRD) with three replications. The data were methodically collected and recorded, and mean differences among the treatments were calculated using Duncan's Multiple Range Test (DMRT) at a 5% probability level (Gomez and Gomez, 1984) using MSTAT C package program.

Preparation of the nutrient solution (NS)

Fertilizers were selected that are compatible with each other. The required amount of Calcium Nitrate and EDTA Iron were mixed into a 10-liter container for the preparation of nutrient solution A and the remaining nutrients were mixed into another 10-liter-sized container for nutrient solution B preparation. Then the nutrients from both containers were mixed into the growth tank according to the assigned treatments.

Nutrient solution for hydroponics and its management

All essential macro and micronutrients based on Cooper's (1979) hydroponic nutrients solution were supplied to hydroponic plants in the form of nutrient solution, which consisted of fertilizer salts dissolved in water. The five pH treatments were assigned as follows: P_1 = pH level 4, P_2 = pH level 5, P_3 = pH level 6, P_4 = pH level 7, P_5 = pH level 8. The pH of the solution was maintained using H_3PO_3 and lower pH levels were maintained using hydrogen phosphate (HPO_4), higher pH levels were maintained using sodium hydroxide (NaOH) throughout the experimental period.

Plant establishment

Initially, seedling production involved the selection of sponge foam measuring 30 cm × 30 cm. Small square cutouts, each measuring 2.5 cm × 2.5 cm, were created in the sponge foam to accommodate seed sowing. Subsequently, a 1 cm cut was made into each of these square-sized foam pieces, and the seeds were sown. After three days of seed germination, each seedling tray received 5-7 ml of nutrient solution. As the seedlings reached 10 to 12 days after germination, they were supplied with 10 ml of nutrient solution daily before being transplanted into larger containers. This transplantation occurred when the seedlings had reached the fourth true leaf stage (Mallick *et al*. 2018).

Each plant was transplanted into a 50-liter plastic bucket, and the volume of the nutrient solution was consistently maintained by periodically adding more nutrient solution throughout the experimental period. Each plastic tank was treated with the respective nutrient solution for each treatment, and this was replicated three times. To monitor and maintain the electrical conductivity (EC) and pH levels of the nutrient solution, measurements were taken at regular intervals using an EC/TDS meter (Hanna, Japan) and a pH meter, respectively. To ensure adequate oxygen levels in the nutrient solution, an aerator and air stone were employed in each plastic tank. Subsequently, the broccoli plants were cultivated in a well-maintained glasshouse.

Data on different parameters were collected during the study and they are as follows:

The total number of leaves on an individual plant was recorded, and the mean value was subsequently calculated. Leaf area was measured using a leaf area meter (LAM-A, Shandong, China) and expressed in square centimeters (cm^2). The shoot length was determined with a meter scale, measured from the base of the plant to the tip of the leaf on the main stem, and expressed in centimeters (cm). Root length was measured using a meter scale, extending from the base of the plant to the end of the root, and expressed in centimeters (cm). For the parameters of the total number of leaves, leaf area, shoot length, and root length, the initial count was taken 15 days after transplanting (DAT), followed by subsequent counts at 30, 45, and 60 DAT.

After harvesting (at 60 DAT), the curd diameter was measured using slide calipers, and the data were recorded in centimeters (cm), with mean values subsequently calculated. The fresh weight of the curd was measured with an electric balance immediately after harvesting, and the data were expressed in grams (g). Following this, the curd was cut into small pieces and subjected to a seven-day oven-drying process at 70 °C. The difference between the fresh and dry weights was measured, and mean values were calculated. The total soluble solids (TSS) content of the broccoli head was determined using a digital refractometer (BOECO, Germany). To assess the total phenolic content, a modified version of the method described by Chanda and Dave (2009) was employed. Titratable acidity was determined following the method outlined by Ranganna (1977). The Vitamin C (Ascorbic acid) content was assessed using the method detailed by Ranganna (1979).

Results and Discussion

Number of leaves per plant

The number of leaves per plant exhibited no significant (p >0.05) variation when subjected to different pH levels, as shown in Table 1. Nevertheless, the highest number of leaves per plant, totaling 14.67, was noted in the pH treatment denoted as P_3, corresponding to a pH level of 6 at 60 days after transplanting (DAT). Conversely, at 60 DAT, the lowest number of leaves per plant was observed in the pH treatment labeled as P_1, which maintained a pH level of 4.0. Silva *et al*. (2019) also reported a similar outcome, showing no significant pH effect in melon.

Table 1: Influence of different pH levels on the number of leaves per plant of broccoli.

Treatments	Number of leaves per plant			
	15 DAT	30 DAT	45 DAT	60 DAT
P_1	8.33	13.00	12.00	13.33
P_2	9.00	13.67	13.67	14.33
P_3	9.33	14.33	15.67	14.67
P_4	9.00	13.33	15.33	14.33
P_5	8.67	13.33	14.67	14.00
LSD 0.05	NS	NS	NS	NS

Here, P_1 = pH level 4, P_2 = pH level 5, P_3 = pH level 6, P_4 = pH level 7, P_5 = pH level 8. Numbers in columns followed by different letters differ significantly, but common letter (s) do not differ significantly. NS = not significant.

Leaf area

Significant (p <0.05) differences in leaf area were observed at different growth stages of the broccoli plants when they were exposed to various pH levels, as illustrated in Figure 1. The leaf area of the broccoli plants exhibited a consistent increase as the experimental period progressed. The findings indicated that the highest leaf area, measuring 407.42 cm², was associated with the pH treatment P_3 (pH level 6.0) at 60 days after transplanting (DAT). This outcome significantly diverged from all other treatments, while the lowest leaf area, at 335.23 cm², was observed in the pH treatment P_5 (pH level 8). Kudirka *et al*. (2023) observed the highest leaf area in lettuce when cultivated in a nutrient solution with a pH range of 6.0-6.5, which supports our findings.

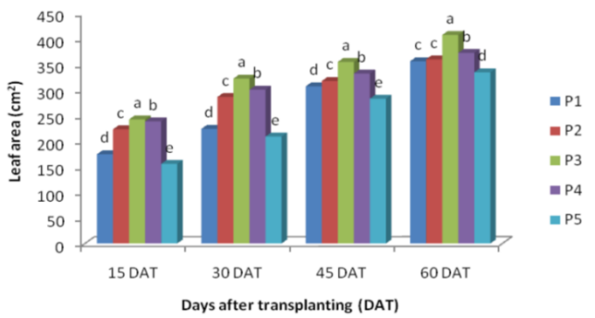

Figure 1. Leaf area of broccoli as affected by different pH Levels (P_1 = pH level 4, P_2 = pH level 5, P_3 = pH level 6, P_4 = pH level 7, P_5 = pH level 8). Graphs followed by different letters differ significantly, but common letter (s) do not differ significantly.

Shoot length

The shoot length of the broccoli plant exhibited a significant (p <0.05) response to varying pH levels at all growth stages, as depicted in Figure 2. As the experimental period advanced, the shoot length of the broccoli plant consistently increased. The findings revealed that the highest shoot length, measuring 28.77 cm at 60 days after transplanting (DAT), was attained with the pH treatment P_3 (pH level 6). It's noteworthy that this result demonstrated statistical similarity to the performance of P_2 (pH level 5) across all growth stages. In contrast, the lowest shoot length for broccoli, at 19.83 cm at 60 DAT, was recorded for the pH treatment P_5 (pH level 8). In a previous study, Rajatha *et al*. (2019) reported the highest shoot length in tomatoes with a pH range of 6.0-6.4 when cultivated in an aeroponic system.

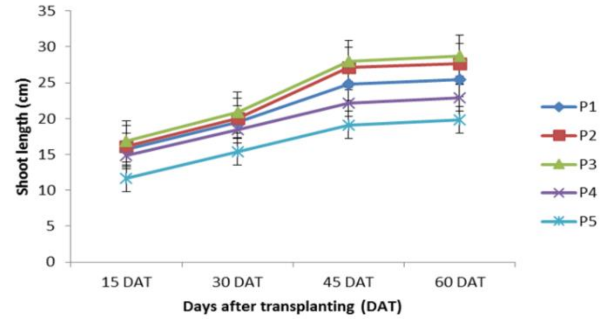

Figure 2. Shoot length of broccoli as affected by different pH Levels (P_1 = pH level 4, P_2 = pH level 5, P_3 = pH level 6, P_4 = pH level 7, P_5 = pH level 8). Vertical bars represent the standard error of the mean.

Root length

Different pH levels exhibited a significant (p <0.05) influence on the root length of broccoli at various growth stages, as illustrated in Figure 3. A consistent upward trend in the root length of the broccoli plant was evident throughout the experiment. The greatest root length for broccoli, measuring 32.0 cm at 60 days after transplanting (DAT), was recorded in the pH treatment P_3 (pH level 6). This result showed significant divergence from the outcomes of the other treatments. Conversely, the lowest root length for broccoli, at 23.0 cm at 60 DAT, was linked to the pH treatment P_5 (pH level 8). In the aeroponic system, tomatoes exhibited higher root length when grown in a nutrient solution with a pH range of 6.0-6.4, as reported by Rajatha *et al*. (2019). The pH of the nutrient solution significantly influences plant growth as it affects nutrient availability and uptake through the plasma membrane. Determining whether growth inhibition and nutrient disorders observed at low pH result from the direct impact of excessive hydronium ion concentration or pH-dependent factors influencing nutrient availability and uptake is challenging. Nevertheless, research suggests that the direct influence of pH appears to be detrimental primarily at the extreme ends of acidity and alkalinity. Growth reductions and nutrient disorders outside the conventional pH ranges are typically attributed to pH-dependent factors (Arnon and Johnson, 1942; Bugbee, 2004; Gillespie *et al*. 2020; Islam *et al*., 1980; Mengel *et al*. 2001; Vlamis, 1953). Nutrients such as Ca, P, Fe, and Mn were identified as potentially restricted at high pH due to precipitation into insoluble salts (Resh, 2004). Moreover, the lower nutrient solution pH values (e.g., the level of pH = 4.0) is also reported to impair plant growth and biomass accumulation by reducing photosynthetic rate due to lower transpiration rate and closure of leaf stomata in tomato seedlings (Kang *et al*. 2011).

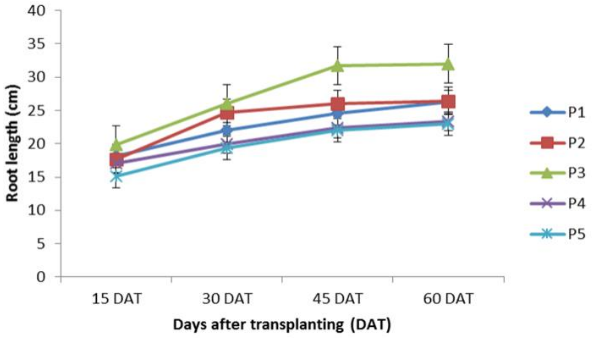

Figure 3. Root length of broccoli as affected by different pH Levels (P_1 = pH level 4, P_2 = pH level 5, P_3 = pH level 6, P_4 = pH level 7, P_5 = pH level 8). Vertical bars represent the standard error of the mean.

Physical characteristics of broccoli curd

Curd diameter

Various pH treatments had a significant (p <0.05) impact on curd diameter, as indicated in Table 2. The most considerable curd diameter, measuring 14.83 cm, was observed in the pH treatment P_3 (pH level 6). In contrast, the pH treatment P_1 (pH level 4) resulted in the smallest curd diameter, measuring 8.83 cm.

Curd fresh weight

Significant (p <0.05) differences in curd fresh weight were observed, and these variances were influenced by distinct pH levels, as indicated in Table 2. The results demonstrated that the pH treatment P_3 (pH level 6) produced the most substantial curd fresh weight, measuring 242.33 grams, which exhibited a significant (p <0.05) disparity from the outcomes of the other treatments. Conversely, the pH treatment P_1 (pH level 4) yielded the smallest curd fresh weight, registering at 76.67 grams. From the table, it is observed that the highest yield of broccoli was obtained in P_3. The yield of early marketable cucumber fruit was higher at pH 5 compared to pH 8, as observed by Tyson *et al*. (2008). Lettuce demonstrated a 17% increase in yield when the nutrient solution was maintained within the pH range of 6.0–6.5, as reported by Kudirka *et al*. (2023).

Curd dry weight

The curd dry weight of broccoli was notably (p <0.05) affected by varying pH levels, as illustrated in Table 2. The pH treatment P_3 (pH level 6) produced the highest curd dry weight at 28.33 g, demonstrating a significant difference from the other treatments. Conversely, the pH treatment P_1 (pH level 4) resulted in the lowest curd dry weight at 9.80 g.

Table 2: Influence of different pH levels on the broccoli curd diameter, fresh weight and dry weight.

Treatments	Curd diameter (cm)	Curd fresh weight (g)	Curd dry weight (g)
P_1	8.83 d	76.67 d	9.80 d
P_2	10.80 c	102.33 c	11.17 c
P_3	14.83 a	242.33 a	28.33 a
P_4	13.33 b	133.67 b	15.47 b
P_5	11.20 c	131.33 b	14.93 b
LSD 0.05	0.71	5.31	0.65
CV (%)	4.78	7.21	5.03

Here, P_1 = pH level 4, P_2 = pH level 5, P_3 = pH level 6, P_4 = pH level 7, P_5 = pH level 8. Numbers in columns followed by different letters differ significantly, but common letter (s) do not differ significantly.

Total Soluble Solids (TSS)

Various pH levels did not exert a significant (p >0.05) influence on TSS content, as presented in Table 3. However, the pH treatment P_3 (pH level 6) did yield the highest TSS content at 6.17%, while the lowest TSS content, at 5.18%, was associated with the pH treatment P_1 (pH level 4). In contrast to our findings, Alexopoulos *et al*. (2021) reported a significant increase (22.0%) or a trend of increase in total soluble solids content in the leaves of both *Reichardia picroides* and *Taraxacum officinale* when grown at a lower pH (4.0) compared to a higher pH (7.0).

Phenols

The variations in pH levels, as outlined in Table 3, did not result in a significant (p >0.05) impact on phenol content. Nevertheless, the pH treatment P_3 (pH level 6) displayed the highest phenol content at 7.23%, while the pH treatment P_1 (pH level 4) exhibited the lowest phenol content at 6.30%. Contrary to our results, Alexopoulos *et al*. (2021) reported a significantly higher (26.9%) total phenolic content in *Reichardia picroides* plants grown at a lower pH (4.0) compared to a higher pH (7.0).

Titratable Acidity

Diverse pH levels, as indicated in Table 3, did not significantly (p >0.05) affect titratable acidity. However, the pH treatment P_3 (pH level 6) recorded the highest titratable acidity at 0.46, while the pH treatment P_1 (pH level 4) displayed the lowest titratable acidity at 0.34. On the contrary, Alexopoulos *et al*. (2021) noted a significant increase (26.9%) in titratable acidity (TA) at pH 4.0 compared to pH 7.0 in *Taraxacum officinale* and *Reichardia picroides*.

Vitamin C Content

Vitamin C content was significantly (p >0.05) influenced by different pH levels (Table 3). The results revealed that the highest vitamin C content, measuring 80.67 mg/100 g of fresh tissue, was obtained from the pH treatment P_3 (pH level 6), while the lowest vitamin C content, at 77.53 mg/100 g of fresh tissue, was associated with the pH treatment P_1 (pH level 4). It's worth noting that this outcome was statistically identical to those of P_2 (pH level 5) and P_4 (pH level 7). In contrast to our findings, Wang *et al*. (2015) observed an increase in Vitamin C content in water spinach when grown at higher pH (7.0). This might be due to the fact that the effect of nutrient solution pH on the plants depends on the species and the characteristics measured (Silva *et al*. 2019).

Table 3: Influence of different pH levels on biochemical properties of broccoli curd.

Treatments	TSS (%)	Total phenols (%)	Titratable acidity (%)	Vitamin C content (mg/100 g fresh tissue)
P_1	5.18	6.30	0.34	77.53 b
P_2	5.37	6.53	0.43	77.60 b
P_3	6.17	7.23	0.46	80.67 a
P_4	5.77	6.77	0.38	78.33 b
P_5	5.53	6.70	0.37	77.57 b
LSD 0.05	NS	NS	NS	1.17
CV (%)	4.08	5.01	3.04	5.28

Here, P_1 = pH level 4, P_2 = pH level 5, P_3 = pH level 6, P_4 = pH level 7, P_5 = pH level 8. Numbers in columns followed by different letters differ significantly, but common letter (s) do not differ significantly. NS = not significant.

Conclusion

This research investigated five distinct pH treatments. Based on observations related to growth and curd characteristics, it became evident that broccoli plants exhibit superior growth when the pH level is maintained at 6.0 (P_3). When the pH level in the nutrient solution rises to 7.0 or higher, it restricts nutrient availability due to precipitation, leading to imbalances and reduced growth. Conversely, a lower pH of 4.0 inhibits broccoli's growth and development by limiting nutrient availability, resulting in deficiencies. The findings of this study have significantly advanced our understanding of how varying pH levels within nutrient solutions impact broccoli plants. This provides valuable insights into optimizing nutrient solutions, thereby enhancing both production and quality in hydroponic cultivation.

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