



## Optimising electrical conductivity, pH and cultivar selection to enhance yield and nutritional quality of hydroponic lettuce (*Lactuca sativa*) in subtropical environments

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### ABSTRACT

The present study was carried out during 2022–23 and 2023–24 at ICAR-Central Institute for Subtropical Horticulture, Lucknow, Uttar Pradesh to evaluate the combined effects of electrical conductivity (EC), nutrient solution pH and cultivar on growth, yield and quality of hydroponic lettuce (*Lactuca sativa* L.) under subtropical conditions. The experiment was laid out in a factorial completely randomised design (F-CRD) comprising three EC levels (1.8, 2.0 and 2.2 dS/m), three pH levels (5.5, 6.5 and 7.5) and seven lettuce varieties [Bingo (C<sub>1</sub>), Tango (C<sub>2</sub>), Lollo Rosso (C<sub>3</sub>), Grand Rapids (C<sub>4</sub>), Summer Star (C<sub>5</sub>), Romaine (C<sub>6</sub>) and Black Rose (C<sub>7</sub>)] arranged in three replications. The results revealed that increasing EC significantly improved vegetative growth, biomass, yield and quality traits, with EC 2.2 dS/m recording maximum yield, antioxidant capacity, carotenoids and ascorbic acid. Nutrient solution pH markedly influenced nutrient uptake and performance, with pH 6.5–7.5 proving superior depending on EC level. Cultivars responded differentially; ‘Bingo’ produced the highest yield while ‘Black Rose’ exhibited superior nutritional quality. Significant EC × pH × cultivar interactions highlighted the need for cultivar-specific nutrient management. Overall, EC 2.2 dS/m at pH 7.5 was optimal for high productivity and quality of hydroponic lettuce under subtropical environments.

**Keywords:** Antioxidants, Electrical conductivity, Hydroponics, Lettuce, Subtropical agriculture

Hydroponics has emerged as a sustainable and efficient method for vegetable production in subtropical regions where land and water scarcity limit traditional agriculture. Lettuce (*Lactuca sativa* L.), a high-value leafy vegetable is particularly well-suited to hydroponic systems due to its rapid growth cycle adaptability to soilless cultivation and rich nutritional profile which includes antioxidants, vitamins A and C and dietary fiber (Khan *et al.* 2025). Consistent productivity and quality in hydroponic lettuce require precise regulation of nutrient solution parameters, especially electrical conductivity (EC) and pH, which govern nutrient availability, plant metabolism and physiological processes (Kappel *et al.* 2021). As EC represents the ionic concentration in the nutrient solution, it is directly related to nutrient and water uptake. Ideal levels of EC change with the cultivar, stage of growth and environmental conditions (Singh and Rajan 2022). The growing media temperature root zone significantly affects nutrient uptake; higher temperatures in the root zone may necessitate a

lower electrical conductivity (EC) in the nutrient solution while lower temperatures might require a higher EC to ensure adequate nutrient availability. Warmer temperatures can increase nutrient uptake, potentially leading to nutrient toxicity while cooler temperatures can hinder uptake causing deficiencies (Madeline *et al.* 2024). Higher EC levels (2.0–2.5 dS/m) may increase yield but could also affect quality characteristics including vitamin C content, especially under warmer temperatures when stomatal conductance is depleted (Kappel *et al.* 2021). On the contrary, decreased EC has been correlated with increased antioxidant content, such as anthocyanins, polyphenols and flavonoids, especially under moderate to high light regimes, as is the case in subtropical regions (Song *et al.* 2020).

pH critically affects nutrient solubility and availability with the ideal range for hydroponic lettuce being 5.5–6.5. Deviations may cause precipitation of key nutrients like Fe, Mn, Ca and Mg limiting uptake even under optimal EC (Yang *et al.* 1998). Seasonal variation further influences management; lower EC is effective in summer for reducing oxidative stress while higher EC promotes growth and maintains phytochemical content under cooler and optimal temperatures (Song *et al.* 2020). The lettuce varieties plays an important role in nutrient uptake efficiency, leafy growth

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and phytochemical accumulation. Variability in varietal responses to EC and pH causes difficulty in standardising nutrient management practices.

Despite extensive research on hydroponic lettuce, critical gaps remain in the integrated optimisation of electrical conductivity (EC), pH and varietal performance under subtropical conditions, where high temperatures and intense radiation substantially affect nutrient availability and plant physiological functioning. Most existing recommendations are derived from temperate environments and evaluate EC and pH independently thereby neglecting their interactive effects on vegetative growth, biomass accumulation, marketable yield and quality attributes. Furthermore, cultivar-specific responses to EC–pH regimes in terms of growth vigour, yield stability and quality parameters are poorly documented under subtropical conditions. This study addresses these gaps by systematically assessing combined EC and pH levels across lettuce cultivars, generating region-specific and cultivar-responsive nutrient management strategies aimed at optimising growth, yield and nutritional quality in subtropical hydroponic systems.

#### MATERIALS AND METHODS

The present study was carried out during 2022–23 and 2023–24 at ICAR-Central Institute for Subtropical Horticulture (26°45′–27°10′ N, 80°30′–80°05′ E; at 123 m amsl), Lucknow, Uttar Pradesh.

A three-factor factorial completely randomised design (F-CRD) with three replications was adopted to study the interactive effects of nutrient solution pH, electrical conductivity (EC) and lettuce varieties on growth, yield and quality. Treatments included three EC levels, viz. 1.8 dS/m ( $E_1$ ), 2.0 dS/m ( $E_2$ ) and 2.2 dS/m ( $E_3$ ); three pH levels: 5.5 ( $P_1$ ), 6.5 ( $P_2$ ) and 7.5 ( $P_3$ ); and seven lettuce varieties: Bingo ( $C_1$ ), Tango ( $C_2$ ), Lollo Rosso ( $C_3$ ), Grand Rapids ( $C_4$ ), Summer Star ( $C_5$ ), Romaine ( $C_6$ ) and Black Rose ( $C_7$ ) totaling 63 treatment combinations. The ICAR-CISH double-row vertical NFT-based system (Singh and Rajan 2022, Patent Office, Government of India 2023) was employed comprising nine units with four tiers and 24 growing channels each. These open-field NFT (nutrient film technique) setups replicated field-like conditions while ensuring controlled soilless cultivation with continuous nutrient flow for adequate root nutrition and aeration. Seedlings were raised in month of September using 2-inch net pots filled with cocopeat, vermiculite and perlite (3:2:1). Seeds of each cultivar were sown under partial shade with misting for uniform germination. After 30 days, seedlings were transplanted into the NFT system. The nutrient solution, a 3X concentrated ICAR–CISH formulation for leafy vegetables, supplied 13 essential nutrients, N (116 ppm), P (22 ppm), K (201 ppm), Ca (70 ppm), Mg (5 ppm), S (50 ppm), Mn (0.5 ppm), Zn (0.33 ppm), Cu (0.05 ppm), B (0.03 ppm), Fe (1.5 ppm) and Mo (0.03 ppm). EC was maintained by adjusting nutrient stock or diluting water while pH was regulated using diluted  $H_2SO_4$  to lower down the pH or potassium hydroxide (KOH) to raise it.

At harvest plant height, leaf number, leaf length and width, individual leaf weight, stem diameter, shoot and root weight and total yield per plant as well as quality traits including total antioxidant capacity, total carotenoids and ascorbic acid content were recorded. Ascorbic acid was estimated using a Nano Drop spectrophotometer following Nielsen (2017), antioxidant capacity by Rubio *et al.* (2016) and carotenoids as per Yang *et al.* (1998). Data were statistically analysed using SAS software (version 9.4), with ANOVA applied and treatment means compared by LSD at a 5% significance level.

#### RESULTS AND DISCUSSION

The findings of this study highlight the influence of electrical conductivity (EC), pH and cultivar choice on hydroponic lettuce growth, yield and quality in subtropical conditions. Plant growth responded positively to increasing EC levels with growth parameters showing a linear rise from 1.8 to 2.2 dS/m. At 2.2 dS/m, maximum values were achieved for plant height (25.95 cm), number of leaves (19.48), leaf weight (5.92 g), stem diameter (1.24 cm), shoot weight (68.55 g), root weight (27.93 g) and yield/plant (96.47 g). This EC level also yielded the highest antioxidant capacity (416.25  $\mu\text{mol}/100\text{ g}$ ), carotenoids (6.92 mg/100 g) and ascorbic acid (47.15 mg/100 g) (Table 1). Higher EC enhanced nutrient uptake, boosting yield and quality whereas lower EC led to nutrient insufficiency and reduced growth. Previous studies corroborate that low EC inhibits hydroponic lettuce growth (Falovo *et al.* 2009, Samarakoon *et al.* 2019) while optimal EC (1.5–3.5 dS/m) maximises yield depending on crop and climate (Ding *et al.* 2018). Similarly, Neocleous *et al.* (2014) observed increased flavonoids, phenolic acids and carotenoids with elevated EC in lettuce.

Nutrient solution pH also showed significant effects. Growth and yield increased linearly between pH 5.5 and 6.5 with higher leaf numbers, shoot and root weights observed at pH 6.5. Maximum plant height, leaf length and antioxidant levels were noted at pH 5.5 while pH 7.5 gave the highest carotenoid and ascorbic acid content. This aligns with Tyson *et al.* (2008), who linked yield increases at pH 6.5 with better nutrient availability while higher pH reduced uptake efficiency. pH effects were also environment and EC dependent. For instance, Hyun *et al.* (2005) found that rose stems and biomass were highest at pH 8 under EC 1.2 dS/m. Similar pH-dependent responses were noted in hydroponic systems by Samarakoon and Palmer (2020) (Table 1).

Lettuce cultivars displayed distinct performance patterns. Bingo had the highest yield (127.84 g/plant), leaf weight (7.63 g) and shoot biomass while Lollo Rosso achieved maximum plant height (31.53 cm), leaf number (19.69) and root weight (35.68 g). Grand Rapids recorded the longest leaves (27.70 cm) and widest lamina (15.81 cm). Black Rose excelled in nutritional quality, producing maximum antioxidants (740.06  $\mu\text{mol}/100\text{ g}$ ), carotenoids (7.36 mg/100 g) and ascorbic acid (61.59 mg/100 g). These

Table 1 Effect of different EC concentration and pH levels on yield and quality of hydroponic lettuce

Treatment	Yield (g/plant)	Plant height (cm)	No. of leaves/plant	Leaf length (cm)	Leaf width (cm)	Leaf weight (g)	Stem diameter (mm)	Average shoot weight (g)	Average root weight (g)	Total antioxidant (µmol/100 g)	Carotenoids (mg/100 g)	Total ascorbic acid (mg/100 g)
EC level												
E <sub>1</sub>	71.34	24.78	12.88	23.60	12.49	5.06	0.91	54.43	20.01	311.17	6.09	38.15
E <sub>2</sub>	88.10	24.89	16.14	20.46	14.69	5.70	1.16	64.75	25.55	254.55	6.64	43.21
E <sub>3</sub>	96.47	25.95	19.48	19.80	15.24	5.92	1.24	68.55	27.93	416.25	6.92	47.15
pH Level												
P <sub>1</sub>	82.38	25.42	15.16	25.26	14.36	5.57	1.06	60.77	19.93	272.34	6.91	41.78
P <sub>2</sub>	91.35	24.14	17.44	19.56	14.47	6.09	1.15	68.35	28.41	264.45	6.85	41.03
P <sub>3</sub>	82.18	23.05	15.90	19.03	13.58	5.01	1.11	58.61	25.14	270.15	5.78	35.69
CD (p=0.05)	0.803	0.33	0.32	0.38	0.298	0.195	0.044	1.301	0.978	1.863	0.081	0.27
SE(d)	0.406	0.167	0.16	0.19	0.151	0.099	0.022	0.657	0.494	0.941	0.041	0.137
SEM±	0.287	0.118	0.11	0.13	0.106	0.07	0.016	0.465	0.349	0.665	0.029	0.097

Treatment details are given under Materials and Methods.

differences may be attributed to inherent genetic variability among the cultivars and are in agreement with the findings of Gualberto *et al.* (2018), who observed significant differences in morphology, yield and nutritional traits among hydroponic lettuce genotypes (Table 2).

Interactive effects of EC and pH significantly influenced growth and quality. The E<sub>3</sub>P<sub>3</sub> combination (EC 2.2 dS/m, pH 7.5) gave the highest yield (101.5 g/plant), leaf number (20.89), average leaf weight (6.09 g), stem diameter (1.42 cm) and antioxidant activity (633.28 µmol/100 g). Conversely, E<sub>2</sub>P<sub>3</sub> (EC 2.0 dS/m, pH 7.5) recorded the tallest plants (27.27 cm) and highest shoot weight (70.91 g). Serio *et al.* (2001) similarly noted increased fresh weight when EC was reduced from 3.5 to 1.5 dS/m, supporting the sensitivity of growth traits to combined EC and pH levels. (Supplementary Table 1)

EC and cultivar interactions were equally important. The best yield (162.11 g/plant) was achieved under E<sub>3</sub>C<sub>1</sub> (EC 2.2 dS/m with Bingo) while E<sub>3</sub>C<sub>3</sub> (EC 2.2 dS/m with Lollo Rosso) gave the highest leaf number (22.64), stem diameter (1.41 cm) and root biomass (39.94 g). Nutritional quality peaked in Black Rose at EC 2.2 dS/m, producing antioxidants up to 884.76 µmol TE/100 g, in line with findings by Kim *et al.* (2008), who reported elevated phenolic and antioxidant levels in lettuce under high EC (Supplementary Table 2). Intermediate EC levels, however promoted higher ascorbic acid and carotenoids, suggesting a balance between nutrient sufficiency and mild stress. Song *et al.* (2020) highlighted that moderate EC levels under strong light induce anthocyanins, flavonoids and polyphenols improving nutritional quality in subtropical systems. This “nutritional eustress” concept (Scuderi *et al.* 2011, Santos

Table 2 Effect of different varieties on yield and quality of hydroponic lettuce

Treatment	Yield (g/plant)	Plant height (cm)	No. of levels/plant	Leaf length (cm)	Leaf width (cm)	Leaf weight (g)	Stem diameter (mm)	Average shoot weight (g)	Average root weight (g)	Total antioxidant (µmol/100 g)	Carotenoids (mg/100 g)	Total ascorbic acid (mg/100 g)
Varieties												
C <sub>1</sub>	127.84	22.84	16.42	20.64	17.51	7.63	1.04	102.34	25.50	178.85	4.82	29.40
C <sub>2</sub>	59.31	25.43	17.13	20.78	8.15	3.02	0.96	38.64	20.67	157.38	6.54	33.00
C <sub>3</sub>	110.35	31.53	19.69	24.66	12.80	5.23	1.23	74.67	35.68	239.85	6.32	34.34
C <sub>4</sub>	91.41	26.27	16.50	27.70	15.81	5.47	1.11	64.69	26.72	284.09	6.67	32.98
C <sub>5</sub>	94.26	25.37	15.08	19.69	15.11	6.46	1.27	68.56	25.70	125.69	6.61	30.58
C <sub>6</sub>	64.29	19.00	15.06	17.78	15.25	5.36	1.14	45.96	18.33	565.33	6.35	54.64
C <sub>7</sub>	62.04	18.99	13.28	17.75	14.34	5.75	1.00	43.19	18.85	740.06	7.36	61.59
CD (p=0.05)	1.226	0.50	0.49	0.57	0.455	0.298	0.067	1.988	1.494	2.846	0.123	0.413
SE(d)	0.62	0.26	0.25	0.29	0.230	0.151	0.034	1.004	0.755	1.422	0.062	0.209
SEM±	0.438	0.18	0.18	0.21	0.163	0.106	0.024	0.71	0.534	0.711	0.044	0.147

Treatment details are given under Materials and Methods.

*et al.* 2024) explains how moderate EC sustains yield while enhancing secondary metabolism leading to improved post-harvest quality and resilience. Overall, the findings suggest that optimising EC in the range of 1.8–2.2 dS/m is most beneficial for maximising yield and maintaining desirable quality under subtropical hydroponic conditions. Slightly elevated EC may be strategically applied when the goal is to enrich antioxidant and phenolic content whereas very low or excessively high EC levels should be avoided as they compromise either yield or market quality. Kim *et al.* (2016), also reported the dual role of EC in regulating productivity and nutritional quality of lettuce. The present work thus reinforces the importance of precise nutrient management in hydroponics where fine-tuning EC not only enhances productivity but also improves functional attributes of lettuce making the crop more suitable for health-conscious consumers.

pH and cultivar interactions also influenced outcomes. P<sub>3</sub>C<sub>1</sub> (pH 7.5, Bingo) delivered the maximum yield (154.29 g/plant), leaf width (19.15 cm) and shoot weight (138.47 g) while P<sub>3</sub>C<sub>3</sub> (pH 7.5, Lollo Rosso) achieved maximum

plant height (31.78 cm), leaf number (21) and root biomass (42.73 g). Black Rose at pH 6.5 (P<sub>2</sub>C<sub>7</sub>) gave the highest antioxidant activity (1115.22 µmol/100 g), carotenoids (7.79 mg/100 g) and ascorbic acid (61.39 mg/100 g). The superior performance of Bingo at pH 7.5 suggests genetic adaptation for nutrient uptake at higher pH while the red-pigmented Black Rose benefited from optimal nutrient availability at pH 6.5 consistent with Alexopoulos *et al.* (2021), who found enhanced pigment and antioxidant accumulation in red-leaf cultivars under favourable pH (Supplementary Table 3). Although, optimum yield is frequently reported at pH 6.0–6.5 at certain EC. The observed variation in yield across pH levels under different EC regimes reflects a strong pH × EC interaction, indicating that the optimum pH in hydroponics is dependent on nutrient strength rather than fixed. Studies have shown that under higher EC, increased ionic concentration alters nutrient speciation, osmotic potential and rhizosphere buffering, shifting the pH optimum toward neutral to slightly alkaline conditions. Savvas and Gruda (2018) reported that elevated EC can widen the optimal pH range by stabilising nutrient uptake and reducing ion antagonism

Table 3 Interaction effect of different pH, EC levels of nutrient solution and varieties on yield and quality of hydroponic lettuce

Treatments	Yield (g/plant)	Plant height (cm)	No. of leaves/plant	Leaf length (cm)	Leaf width (cm)	Leaf weight (g)	Stem diameter (mm)	Average shoot weight (g)	Average root weight (g)	Total antioxidant (µmol/100 g)	Carotenoids (mg/100 g)	Total ascorbic acid (mg/100 g)
E <sub>1</sub> P <sub>1</sub> C <sub>1</sub>	111.73	20.00	13.40	19.80	15.70	8.20	1.40	91.40	20.33	140.75	5.81	14.80
E <sub>1</sub> P <sub>1</sub> C <sub>2</sub>	62.80	23.67	16.20	18.72	5.53	2.00	0.70	44.00	18.80	241.25	5.53	47.40
E <sub>1</sub> P <sub>1</sub> C <sub>3</sub>	85.40	32.27	14.33	24.75	11.17	4.27	1.17	61.13	24.27	143.24	5.07	36.57
E <sub>1</sub> P <sub>1</sub> C <sub>4</sub>	81.47	25.67	13.27	20.53	17.39	6.27	1.27	17.27	17.27	64.33	7.27	31.68
E <sub>1</sub> P <sub>1</sub> C <sub>5</sub>	28.93	31.57	7.40	18.02	9.52	2.73	0.90	16.67	12.27	107.35	7.19	31.48
E <sub>1</sub> P <sub>1</sub> C <sub>6</sub>	26.00	17.83	9.33	17.38	12.04	2.60	0.53	21.47	9.20	128.87	1.58	22.02
E <sub>1</sub> P <sub>1</sub> C <sub>7</sub>	58.93	19.27	10.73	17.99	13.80	3.33	1.03	48.67	10.27	180.87	3.05	32.19
E <sub>1</sub> P <sub>2</sub> C <sub>1</sub>	98.00	25.43	10.80	21.22	13.81	4.80	0.53	81.33	18.00	608.08	4.71	27.11
E <sub>1</sub> P <sub>2</sub> C <sub>2</sub>	55.47	26.23	15.67	23.71	7.72	3.67	0.77	43.53	11.93	94.94	3.14	21.35
E <sub>1</sub> P <sub>2</sub> C <sub>3</sub>	109.67	34.70	19.60	29.74	12.48	5.93	1.17	85.80	23.87	241.23	5.63	47.16
E <sub>1</sub> P <sub>2</sub> C <sub>4</sub>	96.13	29.70	14.60	20.59	13.65	5.47	1.13	109.00	21.80	238.40	7.73	26.17
E <sub>1</sub> P <sub>2</sub> C <sub>5</sub>	86.60	22.60	10.93	18.70	13.67	6.27	1.00	50.47	17.40	37.61	8.58	26.46
E <sub>1</sub> P <sub>2</sub> C <sub>6</sub>	27.93	19.23	9.53	16.71	11.70	3.60	0.80	23.13	10.87	164.21	7.73	47.37
E <sub>1</sub> P <sub>2</sub> C <sub>7</sub>	58.93	19.27	9.73	16.80	10.66	3.20	1.03	21.67	13.20	108.97	7.09	37.28
E <sub>1</sub> P <sub>3</sub> C <sub>1</sub>	98.00	25.43	13.67	20.53	16.03	6.40	0.63	118.47	22.73	15.32	3.43	32.19
E <sub>1</sub> P <sub>3</sub> C <sub>2</sub>	55.47	26.23	13.93	17.75	5.67	1.80	0.73	21.67	16.37	141.05	4.15	32.19
E <sub>1</sub> P <sub>3</sub> C <sub>3</sub>	109.67	34.70	20.87	24.21	12.50	4.27	0.83	80.33	54.73	261.26	7.02	31.86
E <sub>1</sub> P <sub>3</sub> C <sub>4</sub>	96.13	29.70	14.80	19.58	17.49	8.93	1.13	99.00	44.47	208.34	7.48	16.26
E <sub>1</sub> P <sub>3</sub> C <sub>5</sub>	86.60	22.60	10.93	18.70	14.92	6.87	1.03	66.73	25.60	143.48	5.32	36.35
E <sub>1</sub> P <sub>3</sub> C <sub>6</sub>	44.00	18.77	11.93	16.74	14.70	4.33	0.90	27.60	16.40	261.22	5.14	41.55
E <sub>1</sub> P <sub>3</sub> C <sub>7</sub>	20.33	15.43	8.77	13.47	12.17	11.31	0.50	13.67	10.33	258.06	9.14	31.43
E <sub>2</sub> P <sub>1</sub> C <sub>1</sub>	66.85	20.37	11.67	20.14	14.89	4.78	0.80	49.27	19.25	143.70	7.69	43.16
E <sub>2</sub> P <sub>1</sub> C <sub>2</sub>	40.00	27.90	12.67	23.37	8.39	3.45	0.85	24.23	18.00	162.92	4.97	32.19
E <sub>2</sub> P <sub>1</sub> C <sub>3</sub>	63.15	28.37	15.18	22.22	9.41	3.02	1.10	43.67	19.48	186.33	4.55	37.28

Contd.

Table 3 (Concluded)

Treatments	Yield (g/plant)	Plant height (cm)	No. of leaves/plant	Leaf length (cm)	Leaf width (cm)	Leaf weight (g)	Stem diameter (mm)	Average shoot weight (g)	Average root weight (g)	Total antioxidant ( $\mu\text{mol}/100\text{ g}$ )	Carotenoids (mg/100 g)	Total ascorbic acid (mg/100 g)
E <sub>2</sub> P <sub>1</sub> C <sub>4</sub>	101.02	25.72	16.23	20.24	18.19	5.55	1.30	75.30	28.23	148.89	7.71	38.28
E <sub>2</sub> P <sub>1</sub> C <sub>5</sub>	214.17	31.70	26.80	23.41	20.05	11.37	1.70	175.67	40.13	601.06	7.04	27.11
E <sub>2</sub> P <sub>1</sub> C <sub>6</sub>	87.67	20.77	16.33	19.60	16.19	5.98	1.40	80.07	9.93	252.97	5.34	21.68
E <sub>2</sub> P <sub>1</sub> C <sub>7</sub>	59.20	18.62	10.60	20.29	15.33	4.80	0.87	41.80	19.73	78.25	7.90	21.09
E <sub>2</sub> P <sub>2</sub> C <sub>1</sub>	98.47	18.58	15.27	19.77	17.32	7.22	1.25	78.47	22.00	390.81	7.88	26.32
E <sub>2</sub> P <sub>2</sub> C <sub>2</sub>	46.30	27.37	14.57	17.33	12.83	2.35	0.94	26.80	20.27	651.23	6.17	57.63
E <sub>2</sub> P <sub>2</sub> C <sub>3</sub>	119.20	29.43	18.15	23.33	12.43	4.33	1.30	74.00	45.87	203.29	8.73	42.20
E <sub>2</sub> P <sub>2</sub> C <sub>4</sub>	59.00	23.70	16.35	13.28	13.00	4.17	0.94	33.40	26.87	258.21	7.97	21.37
E <sub>2</sub> P <sub>2</sub> C <sub>5</sub>	89.13	25.30	10.50	18.21	14.27	4.80	1.59	62.13	26.33	68.26	2.19	27.11
E <sub>2</sub> P <sub>2</sub> C <sub>6</sub>	51.20	18.10	17.70	16.59	16.18	6.67	1.30	49.00	26.67	100.37	4.07	31.86
E <sub>2</sub> P <sub>2</sub> C <sub>7</sub>	53.67	15.82	11.68	18.17	14.36	4.84	0.62	34.53	19.80	700.36	7.58	42.12
E <sub>2</sub> P <sub>3</sub> C <sub>1</sub>	138.20	26.17	17.48	21.51	20.31	8.77	1.00	113.40	26.40	106.06	7.57	27.11
E <sub>2</sub> P <sub>3</sub> C <sub>2</sub>	74.30	27.23	20.00	23.29	8.37	3.88	0.97	46.28	27.27	173.62	5.68	15.54
E <sub>2</sub> P <sub>3</sub> C <sub>3</sub>	112.07	35.33	21.13	29.28	12.38	7.10	1.28	79.00	33.40	154.59	7.10	42.15
E <sub>2</sub> P <sub>3</sub> C <sub>4</sub>	83.60	31.60	16.60	19.29	15.47	4.88	1.14	61.67	23.27	133.12	8.68	36.55
E <sub>2</sub> P <sub>3</sub> C <sub>5</sub>	117.35	28.17	19.27	25.02	15.29	7.58	1.30	89.27	30.00	86.18	8.72	36.10
E <sub>2</sub> P <sub>3</sub> C <sub>6</sub>	73.17	22.17	15.93	17.61	18.12	8.02	1.38	51.20	22.47	89.27	8.03	36.78
E <sub>2</sub> P <sub>3</sub> C <sub>7</sub>	102.32	20.20	14.75	17.65	15.68	6.20	1.34	70.60	31.13	115.64	3.32	22.02
E <sub>3</sub> P <sub>1</sub> C <sub>1</sub>	115.60	28.30	17.30	25.07	20.51	10.27	0.81	95.20	21.07	53.45	5.03	37.28
E <sub>3</sub> P <sub>1</sub> C <sub>2</sub>	70.35	26.83	17.60	23.87	9.30	4.50	1.25	52.07	18.20	148.57	5.52	32.19
E <sub>3</sub> P <sub>1</sub> C <sub>3</sub>	179.00	34.50	26.72	27.57	18.51	8.55	1.42	137.07	41.27	176.72	7.40	16.60
E <sub>3</sub> P <sub>1</sub> C <sub>4</sub>	75.93	26.17	16.43	21.17	16.91	5.17	0.70	53.73	15.20	1117.12	6.18	57.73
E <sub>3</sub> P <sub>1</sub> C <sub>5</sub>	72.33	27.27	14.42	21.43	16.12	6.38	0.80	49.00	24.00	109.46	6.26	36.54
E <sub>3</sub> P <sub>1</sub> C <sub>6</sub>	71.18	22.03	16.63	23.27	16.51	6.40	1.07	54.87	18.07	166.29	6.72	52.35
E <sub>3</sub> P <sub>1</sub> C <sub>7</sub>	58.27	25.00	15.00	21.68	16.17	7.52	1.17	43.67	13.52	816.07	5.19	68.76
E <sub>3</sub> P <sub>2</sub> C <sub>1</sub>	144.07	21.33	20.20	16.75	17.91	7.35	1.23	110.00	35.07	257.19	8.51	63.87
E <sub>3</sub> P <sub>2</sub> C <sub>2</sub>	82.00	23.10	23.20	19.37	8.27	2.52	1.10	52.13	30.87	217.81	3.53	57.63
E <sub>3</sub> P <sub>2</sub> C <sub>3</sub>	93.23	29.20	20.20	21.43	12.37	5.02	1.37	55.00	38.20	513.25	4.21	48.46
E <sub>3</sub> P <sub>2</sub> C <sub>4</sub>	91.73	21.05	19.17	17.45	16.13	5.11	1.13	61.27	31.20	744.74	8.57	69.14
E <sub>3</sub> P <sub>2</sub> C <sub>5</sub>	89.48	21.35	17.37	17.42	14.88	5.87	1.40	60.07	30.13	1146.07	7.93	37.28
E <sub>3</sub> P <sub>2</sub> C <sub>6</sub>	72.00	15.70	17.70	15.37	15.23	5.12	1.37	42.27	30.07	1111.90	8.26	68.24
E <sub>3</sub> P <sub>2</sub> C <sub>7</sub>	103.58	16.87	21.00	17.74	16.29	7.00	1.30	76.87	27.60	583.99	8.71	47.23
E <sub>3</sub> P <sub>3</sub> C <sub>1</sub>	226.67	19.92	28.00	20.97	21.12	10.87	1.73	183.53	44.63	158.87	9.30	31.77
E <sub>3</sub> P <sub>3</sub> C <sub>2</sub>	62.00	20.30	20.37	19.61	7.32	2.99	1.30	37.07	24.33	672.69	8.31	68.47
E <sub>3</sub> P <sub>3</sub> C <sub>3</sub>	95.65	25.30	21.00	19.42	13.92	4.55	1.43	56.00	40.07	1392.80	7.55	74.23
E <sub>3</sub> P <sub>3</sub> C <sub>4</sub>	104.20	23.13	21.03	17.22	14.05	3.70	1.20	71.57	32.13	86.03	3.20	74.23
E <sub>3</sub> P <sub>3</sub> C <sub>5</sub>	72.13	17.73	18.13	16.27	17.29	6.33	1.70	47.00	25.47	83.41	6.73	63.39
E <sub>3</sub> P <sub>3</sub> C <sub>6</sub>	84.68	16.43	20.43	16.72	16.55	5.51	1.47	64.00	21.27	1368.88	7.12	62.72
E <sub>3</sub> P <sub>3</sub> C <sub>7</sub>	61.85	20.45	17.27	15.91	14.59	3.58	1.13	37.20	24.07	1201.98	7.10	64.05
CD (p=0.05)	3.67	1.51	1.48	1.72	1.365	0.894	0.201	5.964	4.483	8.537	0.370	1.238
SE(d)	1.85	0.75	0.74	0.87	0.690	0.452	0.101	3.013	2.265	4.313	0.187	0.626
SEM $\pm$	1.31	0.54	0.52	0.61	0.488	0.319	0.072	2.13	1.601	3.05	0.132	0.442

Treatment details are given under Materials and Methods.

while Sambo *et al.* (2019) demonstrated improved nutrient absorption and yield at near-neutral pH under high nutrient strength. Similarly, Hyun *et al.* (2005) observed maximum biomass accumulation at higher pH under specific EC levels supporting the view that slightly alkaline pH under high EC favours proton-coupled ion transport and sustained nutrient uptake resulting in higher yield.

Triple interactions of EC, pH and cultivar were statistically significant. The E<sub>3</sub>P<sub>3</sub>C<sub>1</sub> combination (EC 2.2 dS/m, pH 7.5, Bingo) gave the highest yield (226.67 g/plant), leaf width (21.12 cm) and carotenoid content while E<sub>2</sub>P<sub>3</sub>C<sub>3</sub> produced the tallest plants (35.33 cm) and longest leaves (29.28 cm). Black Rose under E<sub>3</sub>P<sub>3</sub> (2.2 dS/m, pH 7.5) showed maximum antioxidant activity (1392.80 µmol/100 g) and ascorbic acid (74.23 mg/100 g). These interactions highlight how cultivar genetics and nutrient solution parameters synergise to optimise both productivity and quality, supporting earlier findings by Samarakoon and Palmer (2020) and Singh *et al.* (2019) (Table 3). Overall, the study demonstrates that strategic management of EC and pH combined with cultivar choice can significantly enhance hydroponic lettuce production in subtropical climates. For maximising yield, EC 2.2 dS/m at pH 7.5 with Bingo is optimal while for nutritional enhancement, Black Rose at pH 7.5 is preferable. These findings emphasise the dual role of EC in ensuring nutrient sufficiency while inducing mild stress to improve quality and the critical role of pH in nutrient availability. Cultivar-specific responses underline the importance of genotype selection in hydroponic systems. Such integrated recommendations provide a practical framework for growers in subtropical regions to optimise productivity and nutritional quality of lettuce under hydroponics.

The present investigation carried out during 2022–23 and 2023–24 at ICAR-Central Institute for Subtropical Horticulture, Lucknow, Uttar Pradesh revealed that hydroponic lettuce growth, yield and quality under subtropical conditions were significantly influenced by electrical conductivity (EC), pH and cultivar interactions. An EC of 2.2 dS/m proved optimal for maximising biomass, yield and antioxidant attributes. Yield response to pH was EC-dependent with slightly alkaline pH (7.5) enhancing productivity at higher EC levels. Among cultivars, Bingo recorded the highest yield while Black Rose excelled in nutritional quality. The combined treatment of EC 2.2 dS/m, pH 7.5 and cultivar Bingo was identified as the most productive.

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