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Evaluation of yield performance of *Capsicum annuum* (chili) cultivated using a low-cost, sustainable hydroponic system

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Abstract

One of the most pressing global challenges in conventional agriculture is climate change, which adversely affects crop productivity. Global food security is increasingly threatened by shifting climate patterns, depleting groundwater levels, and rapid urbanization. In this context, soilless hydroponics cultivation offers a sustainable solution, requiring minimal inputs, minimizing pesticide and agrochemical use, and enabling resource-efficient water management. This approach allows for climate-resilient production with precisely controlled yields under indoor farming conditions. *Capsicum annuum* (chili), a widely consumed food crop with high nutraceutical value, faces serious cultivation threats due to unpredictable weather fluctuations. This study evaluates the growth performance of *C. annuum* under a low-cost, water-efficient hydroponic system designed for indoor cultivation, utilizing repurposed mineral water bottles as growing units. A comparative assessment between soilless hydroponics and conventional soil-based cultivation was conducted to determine the potential of this system under controlled indoor conditions. The findings indicate that plant growth characteristics, yield performance, and nutraceutical quality were enhanced in the low-cost, non-circulating hydroponic setup. Key physiological parameters, including reactive oxygen species generation and antioxidant activity, were systematically measured. Overall, the results demonstrate that this sustainable hydroponic approach not only contributes to water-efficient, climate-resilient, and space-saving household chili production but also addresses solid waste management by repurposing discarded plastic bottles, thereby aligning with borader environmental sustainability goals.

Keywords: Hydroponics; Yield performance; Indoor cultivation

1. Introduction

With the rapidly growing global population, one of the major challenges today is producing sufficient food to meet rising demands.[1] Urbanization and industrialization are reducing the availability of arable land and water, while climate change and soil degradation further decrease agricultural productivity.[2,3] Open-field cultivation has become increasingly challenging due to adverse climatic conditions, such as extreme heat, delayed monsoons, groundwater scarcity, and natural disasters, especially in climate-sensitive regions.[4,5] These factors contribute to extensive crop losses, malnutrition, and hunger, which ultimately threaten global food security.

In pursuit of maximizing yields, farmers often rely heavily on chemical fertilizers and pesticides. While such practices can increase productivity, they also contribute to severe soil and water pollution, thereby affecting entire ecosystems.[6] The overuse of agrochemicals also leads to bioaccumulation and biomagnification, causing a range of human health complications.[7]

To combat these challenges, soilless agricultural methods are being explored as alternatives, allowing crops to be cultivated without soil, even under indoor conditions.[8] Hydroponics, in particular, has emerged as a promising and relatively accessible solution, enabling crops to grow with their roots suspended in nutrient-rich aqueous solutions.[9]

Despite its advantages, conventional hydroponic systems pose significant challenges for small-scale or resource-constrained users. The high initial setup cost, requiring pumps, nutrient delivery systems, and other infrastructure, can be prohibitive.[10] Moreover, skilled technical expertise is often required to maintain optimal nutrient balance and environmental parameters for consistent growth and yield. In many cases, urban farming is practiced on windowsills, balconies, or rooftops, where space constraints and the need for reliable electricity further hinder the adoption of conventional systems. In addition, because plants in conventional hydroponic setups share a common nutrient medium, any imbalance in solution quality or outbreak of pests and diseases can spread rapidly, whereas household-level systems using individual containers (e.g., one plant per bottle) may mitigate this risk.[11]

Vegetables, second only to cereals, are critical for nutritional security across all cultures due to their central role in daily diets. According to the Food and Agriculture Organization statistics (FAOSTAT),[12] global per capita vegetable consumption reached approximately 150 kg in 2022. To bridge the demand–supply gap in vegetable production caused by adverse climatic conditions and shrinking cultivatable lands, a transition from soil-based to soilless cultivation systems, such as hydroponic systems, may provide a suitable solution. *Capsicum annuum* L. (chili) is one such vegetable with high global demand owing to its culinary versatility, nutritional value, and medicinal properties. FAOSTAT estimates[13] indicate that in 2023, chili was harvested from 2,065,408 ha worldwide, producing approximately 38,310,350 tons, with India contributing 73,914 tons from 8,616 ha. According to FAOSTAT's 2023 report,[14] global chili exports reached 3,891,395 tons, value at US $7,237,728,000, of which India alone exported 82,463 tons, valued at US $56,561,000. Rich in ascorbic acid (vitamin C), chili is particularly valued for its bioactive compound capsaicin (IUPAC: 8-methyl-N-vanillyl-6-nonenamide), which exhibits a wide range of pharmacological effects, including antioxidant and antimicrobial,[15] anti-inflammatory,[16] anticancer,[17] anti-obesity,[18] antidiabetic,[19] cardioprotective,[20] and gastroprotective[21] properties.

In open-field agriculture, chili plants are highly susceptible to unpredictable weather fluctuations, soil-borne pests and diseases, weed competition, and the excessive use of agrochemicals.[22] Consequently, soilless cultivation methods may represent a viable alternative.[23] However, conventional hydroponic systems remain expensive, technical demanding, and dependent on electricity, restricting their large-scale application to a limited number of commercial farms.[24] Although many studies have emphasized the advantages of hydroponics over soil-based systems, a substantial research gap remains concerning the high establishment costs and the need for skilled management of conventional hydroponic systems.

The current study aims to address these challenges by evaluating the yield performance of *C. annuum* using a low-cost, sustainable hydroponic system constructed from locally available and repurposed materials, such as discarded mineral water bottles. This approach requires minimal technical expertise and is especially suited for peri-urban settings and smallholder or household-level cultivation.

2. Materials and methods

2.1. Plant material

C. annuum seeds were generously provided as a research gift by the Department of Horticulture, Bidhan Chandra Krishi Vidyalaya, Mohanpur, West Bengal, India. The experiment was performed at Adamas University (22°44'21.70" N, 88°27'21.43" E) under indoor conditions, utilizing natural sunlight on an open balcony.

2.2. Seed preparation and germination

Seed viability was tested using randomly selected seeds from the stock, and germination percentage was determined following the protocol by Demir and Ellis (1992).[25] Healthy seeds were surface-sterilized using 10% hydrogen peroxide (H_2O_2) for 10 min, followed by 1% calcium hypochlorite for

1 h.[26] Sterilized seeds (n = 100) were placed in plantation trays containing coco peat as the growth medium and were watered periodically. A control group was maintained by planting seeds in soil obtained from a local nursery. Germination percentage was recorded through regular observations. After 10 days, healthy seedlings (4–5 cm in length) were randomly selected from both plantation trays (coco peat and soil) to assess the seedling vigor index (SVI-I), calculated using Equation I:[27]

$$SVI - I = Seedlinglength \times Germinationpercentage \quad (I)$$

2.3. Experimental setup and plant growth monitoring

Discarded plastic bottles of various sizes were thoroughly cleaned and repurposed as nutrient reservoirs to construct a low-cost, non-circulating hydroponic system (Set I) (Figure 1A and B). A conventional hydroponic system, similar to those commonly used in commercial cultivation, was prepared using an opaque container as the nutrient reservoir, equipped with an electric air pump for aeration and plastic net cups (Set II) (Figure 1C). The nutrient solution was prepared by mixing all the required chemicals (Table A1) following the protocol by Hoagland and Arnon.[28]

Forty randomly selected, healthy seedlings germinated in coco peat were transferred to the hydroponic systems: 20 to Set I and 20 to Set II. In Set I, seedling roots were immersed directly in the nutrient solution, while the stem was secured at the bottle opening with cotton plugs. In Set II, the roots were suspended in the nutrient reservoir, whereas the aerial parts were supported above the lid using net cups. Electrical conductivity (EC) and pH of the nutrient solution were maintained at 1.4–1.8 mS/cm and 5.8–6.5, respectively.[29] These parameters were monitored using commercially available pH paper and a portable EC meter (AP-IS11A058FBA, Aptechdeals, China) and adjusted as necessary by adding water or nutrients. Both hydroponic systems were maintained indoors under natural sunlight on an open laboratory balcony at Adamas University, with a temperature of 22–27°C, relative humidity (RH) of 75–80%, and light intensity of 1,000–3,000 µmol/m^2/s for approximately 11–13 h/day. A soil-based system (n = 20) served as the control (Set III) (Figure 1D).

In summary, the experiment consisted of three treatments:

- Set I: Low-cost hydroponics using plastic bottles (22–27°C, RH 75–80%, 1,000–3,000 µmol/m^2/s for 11–13 h/day
- Set II: Conventional hydroponics using a nutrient reservoir, net cups, and an electric air pump (same conditions as Set I)
- Set III: Soil-grown plants serving as control (same conditions as Set I).

Data were recorded for shoot height (cm), days to first flowering, days to first fruiting, days to full fruit maturation (red-ripe stage), fruit weight, and total yield per plant. Fruit development was monitored visually, and red, fully matured fruits were harvested. Measurements included individual fruit weight and total yield per plant.

2.4. Comparative analysis of stress response

A comparative study was performed using randomly selected leaves from fruit-bearing plants across all three experimental sets. The following assays were conducted:

- H_2O_2 content: Leaf tissue was extracted in 100 mM potassium phosphate buffer containing 5 mM potassium cyanide, and absorbance was measured at 560 nm[30]
- Lipid peroxidation: Malondialdehyde (MDA) content was quantified, and absorbance was read at 532 nm[31]
- Superoxide dismutase (SOD) activity: Measured at 540 nm using p-nitro blue tetrazolium chloride

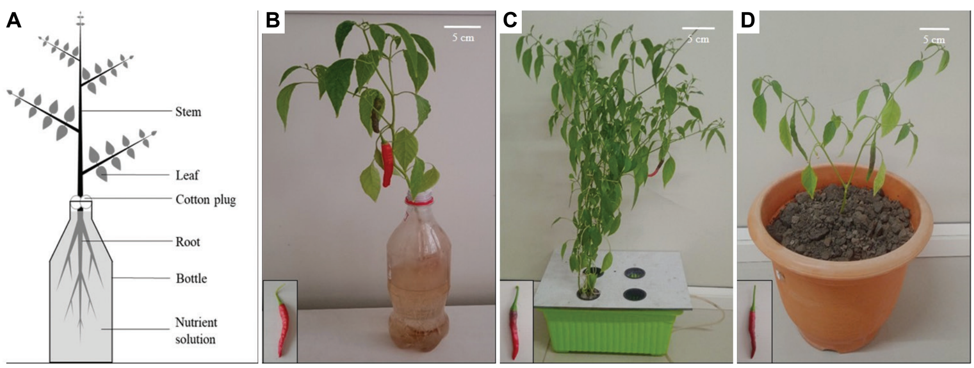

Figure 1. Indoor farming systems: (A) schematic diagram of the low-cost bottle hydroponic system; (B) Set I - plant grown in low-cost hydroponics using a plastic bottle; (C) Set II - conventional hydroponics with nutrient reservoir, net cups, and electric air pump; (D) Set III - soil-grown control plants. Harvest fruits from each system are shown in the corresponding insets.

(NBT). One unit of SOD activity was defined as the amount of enzyme required to inhibit 50% of NBT photoreduction[32]

- Catalase (CAT) activity: Leaf extracts were prepared in the presence of 50 mM phosphate buffer and 20 mM H_2O_2, and absorbance was monitored at 240 nm. One unit of CAT activity was defined as the amount of H_2O_2 decomposed (in μmol) per minute.[33]

2.5. Nutritional quality analysis

Nutritional quality was assessed in randomly selected mature fruits from all three experimental sets by estimating vitamin C and capsaicin content.

- Vitamin C: Fresh fruits were homogenized in 0.4% oxalic acid, and ascorbic acid content was quantified spectrophotometrically at 520 nm following reaction with 2,6-dichlorophenolindophenol[34]
- Capsaicin: Shade-dried fruits were extracted in ethyl acetate, and the absorbance of the extract was measured at 280 nm to determine capsaicin yield.[35]

2.6. Correlation analysis of stress responsiveness and yield performance

Correlation analyses were performed using RStudio (version 2024.12.1+563; posit.co/products/open-source/rstudio) to evaluate the correlations between oxidative stress generation (H_2O_2, MDA), antioxidant enzyme activities (SOD, CAT), yield traits (fruit number, fruit weight, and total yield), and nutritional quality parameters (Vitamin C, capsaicin content). Kendall's tau (τ) correlation coefficient was employed to measure the strength and direction of associations. The statistical significance of correlations was tested using Kendall's tau rank correlation method.

2.7. Usability assessment

A detailed demonstration and hands-on training for the low-cost hydroponic system was conducted on the university campus with 20 underprivileged households, each represented by one member recommended by the local administration (Figure A1). Participants were provided with a basic setup, user manuals written in local languages, and 1 month of cultivation experience. Their feedback was collected to assess the system's accessibility, technical feasibility, and cost-effectiveness from their perspective.

2.8. Statistical analyses

Experiments were replicated 3 times, and data were analyzed using analysis of variance followed by Duncan's multiple range test at $p<0.05$, performed in Statistical Package for the Social Sciences software (version 17.0.0; IBM, United States).[36]

3. Results

3.1. Evaluation of seedling growth potential

Randomly selected seeds from the stock were viable and demonstrated promising germination in plantation trays with both soil and coco peat as substrates. However, seeds raised in coco peat exhibited slightly higher germination performance (80% in soil vs. 100% in coco peat). After 10 days of germination, comparative analysis revealed that the SVI-I was significantly higher—by approximately 70%—in seeds germinated in coco peat in comparison to those grown in soil (Figure 2 and Table A2).

3.2. Plant growth parameters

As shown in Figure 3, plants grown under conventional hydroponics (Set II) exhibited significantly greater shoot height compared with plants grown in low-cost hydroponics (Set I) or soil (Set III), the latter two showing similar height. In addition, plants in soil (Set III) required significantly more time to reach both first flowering and first fruiting stages than those in the two hydroponic systems (Figure 4). Likewise, the number of days required for complete fruit maturation (red-ripe stage) was significantly higher in Set III compared to Sets I and II (Figure 4).

Fruit traits also differed among systems: Both fruit weight and total yield per plant were significantly higher in Sets I and II, while Set III plants displayed a 50–60% reduction in yield (Figure 5). Overall, Set III consistently underperformed relative to the hydroponic systems across all measured parameters. Between Sets I and II, no significant differences were observed, except for plant height, which was greater in conventional hydroponics (Set II) (Figures 1 and 3; Table A3).

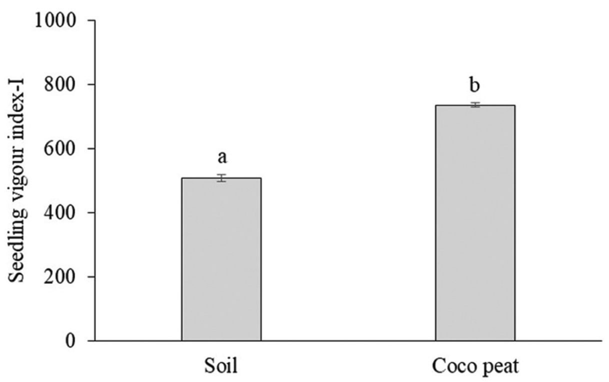

Figure 2. Seedling vigor index-I for soil- versus soilless-grown (coco peat) seedlings. Data were recorded after 10 days of germination and are presented as mean ± standard deviation. Different letters indicate statistically significant differences according to Duncan's multiple range test ($p<0.05$).

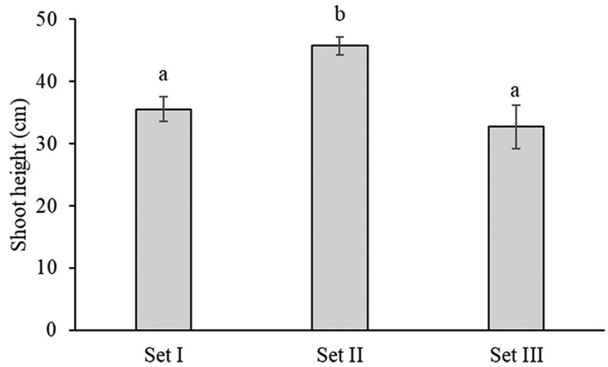

Figure 3. Plant height in the three experimental sets: Set I - low-cost hydroponics using plastic bottles; Set II - conventional hydroponics; Set III - soil control. Data were recorded after 140 days of cultivation and are presented as mean ± standard deviation. Different letters indicate statistically significant differences according to Duncan's multiple range test ($p<0.05$).

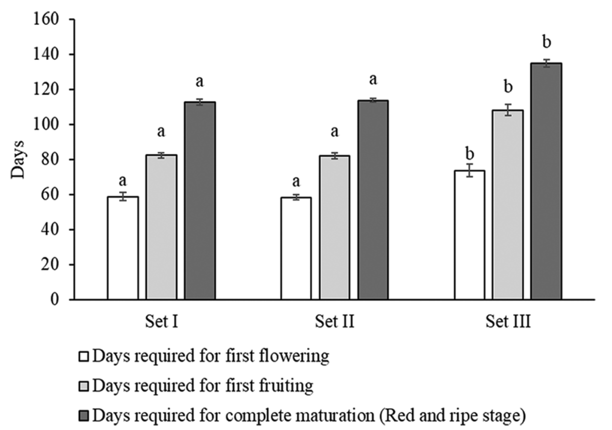

Figure 4. Days required for first flowering, first fruiting, and complete fruit maturation (red-ripe stage) in the three experimental sets: Set I - low-cost hydroponics using plastic bottles; Set II - conventional hydroponics; Set III - soil control. Data are presented as mean ± standard deviation. Different letters indicate statistically significant differences according to Duncan's multiple range test ($p<0.05$).

3.3. Nutritional quality of fruit

Both ascorbic acid and capsaicin contents in mature harvested fruits were significantly higher in plants grown under low-cost hydroponics (Set I) and conventional hydroponics (Set II) compared to soil-grown plants (Set III). As shown in Figure 6, no significant differences were observed between Sets I and II in terms of these nutraceutical parameters (Table A3).

3.4. Physiological response of plants

Leaf peroxide content and MDA levels were two- to threefold higher in soil-grown plants (Set III) compared to either hydroponic systems (Sets I and II) (Figure 7). Conversely, antioxidant enzymatic activities, including SOD and CAT, were nearly twofold lower in Set III plants relative to hydroponic plants (Figure 8). Plants grown under Sets I and II displayed similar physiological responses to stress (Table A4).

3.5. Association analysis of stress responses with yield and nutritional quality traits using Kendall's tau correlation

Kendall's τ correlation analysis (Figure 9 and Table A5) revealed several statistically significant associations between four stress response parameters (H_2O_2, MDA, SOD, and CAT) and three agronomic or nutritional traits (yield, vitamin C content, and capsaicin levels). For yield, significant positive correlations were observed with both SOD ($\tau = 0.77$) and CAT ($\tau = 0.737$), indicating that increased antioxidant enzyme activity is strongly associated with increased yield. Conversely, MDA showed a significant negative correlation ($\tau = -0.604$), suggesting that lipid peroxidation is inversely related to yield. The correlation with H_2O_2 was weak and not statistically significant ($\tau = -0.208$).

For Vitamin C content, moderate positive correlations were detected with SOD ($\tau = 0.567$) and CAT ($\tau = 0.476$), indicating that antioxidant enzymes may play a role in maintaining or enhancing Vitamin C levels. H_2O_2 showed a significant negative correlation ($\tau = -0.385$), suggesting oxidative stress may reduce Vitamin C accumulation. The correlation with MDA was weak ($\tau = -0.206$) and not statistically significant. For capsaicin content, significant positive correlations were detected with SOD ($\tau = 0.648$) and CAT ($\tau = 0.553$). These findings reinforce the pattern observed with yield and Vitamin C, emphasizing the protective or enhancing role of antioxidant enzymes in capsaicin accumulation. Significant negative correlations with H_2O_2 ($\tau = -0.301$) and MDA ($\tau = -0.247$) further indicate that oxidative stress markers may be detrimental to capsaicin synthesis.

3.6. Feedback analysis from local users

More than 60% of participants provided positive feedback on the system's accessibility and cost-effectiveness, while relatively few reported technical difficulties (Figure 10 and Table A6). Overall, the feedback supports the system's practical applicability, affordability, and potential replicability in resource-limited settings.

4. Discussion

The results of the present study clearly demonstrate the potential of hydroponic cultivation practices to enhance plant growth and improve both quality and yield in

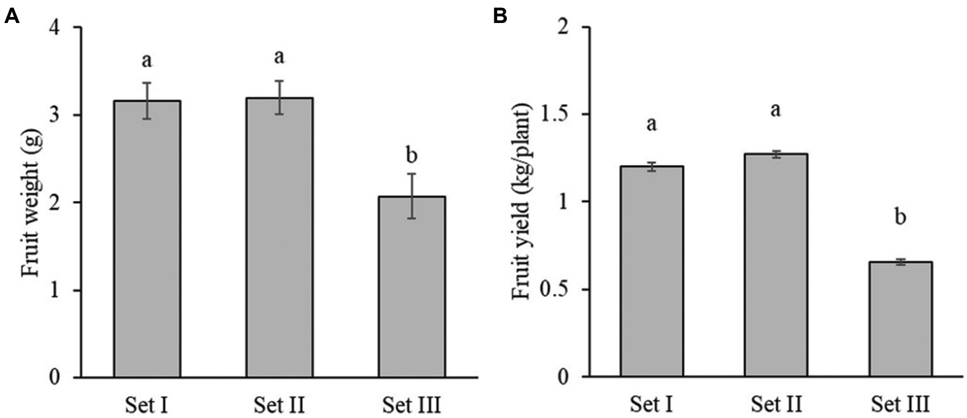

Figure 5. Fruit characteristics in the three experimental sets: (A) average fruit weight; (B) yield per plant. Set I - low-cost hydroponics using plastic bottles; Set II - conventional hydroponics; Set III - soil control. Data are presented as mean ± standard deviation. Different letters indicate statistically significant differences according to Duncan's multiple range test (p<0.05).

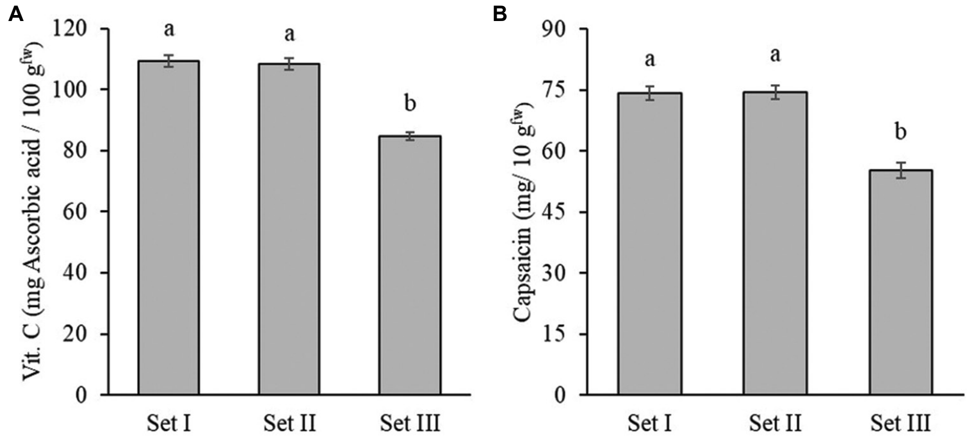

Figure 6. Nutritional quality of fruits in the three experimental sets: (A) Vitamin C (ascorbic acid) content and (B) capsaicin content. Set I - low-cost hydroponics using plastic bottles; Set II - conventional hydroponics; Set III - soil control. Data are presented as mean ± standard deviation. Different letters indicate statistically significant differences according to Duncan's multiple range test (p<0.05).

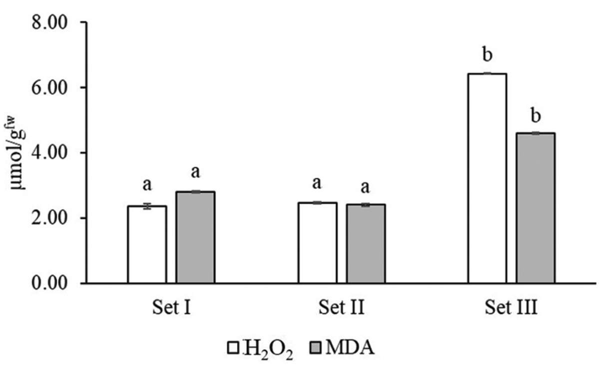

Figure 7. Leaf hydrogen peroxide (H_2O_2) and malondialdehyde contents in mature, fruit-bearing plants from the three experimental sets: Set I - low-cost hydroponics using plastic bottles; Set II - conventional hydroponics; Set III - soil control. Data were recorded after 140 days of cultivation and are presented as mean ± standard deviation. Different letters indicate statistically significant differences according to Duncan's multiple range test (p<0.05).

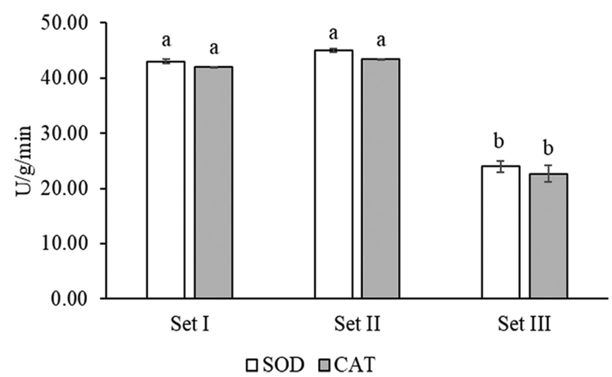

Figure 8. Superoxide dismutase and catalase activity in mature, fruit-bearing plants from the three experimental sets: Set I - low-cost hydroponics using plastic bottles; Set II - conventional hydroponics; Set III - soil control. Data were recorded after 140 days of cultivation and are presented as mean ± standard deviation. Different letters indicate statistically significant differences according to Duncan's multiple range test (p<0.05).

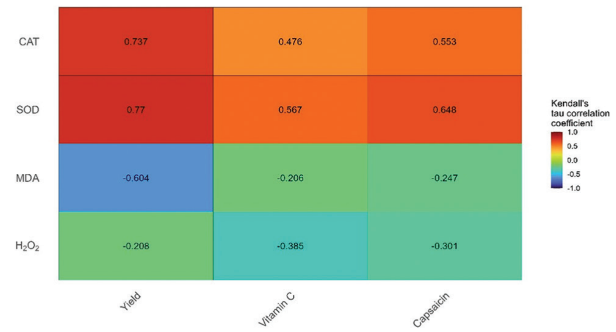

Figure 9. Heatmap of Kendall's tau correlation between oxidative stress markers (H_2O_2, MDA), antioxidant enzymes (SOD, CAT), fruit yield, and nutritional quality traits (vitamin C, capsaicin content). The scale on the right indicates correlation values, with 1 representing a perfect positive correlation, −1 a perfect negative correlation, and 0 no correlation. All values are significant at $p<0.05$.
Abbreviations: CAT: Catalase; H_2O_2: Hydrogen peroxide; MDA: Malondialdehyde; SOD: Superoxide dismutase.

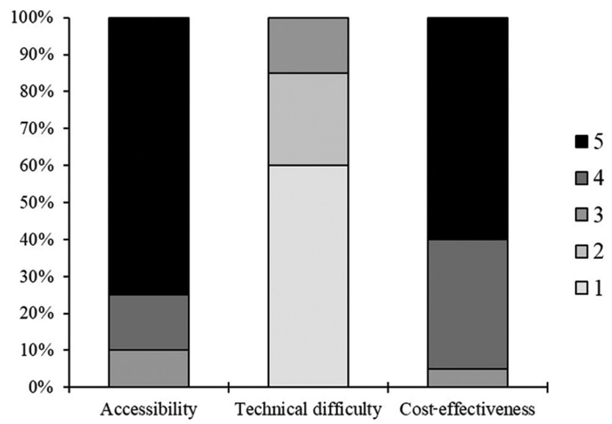

Figure 10. Participant responses (1–5 scale) regarding accessibility, technical difficulty, and cost-effectiveness of the low-cost hydroponic system using plastic bottles

C. annuum while reducing the stress typically experienced by plants grown in soil. Coco peat proved to be a superior germination medium in comparison to soil, most likely due to its higher water-holding capacity. This result is consistent with previous reports, which highlighted the advantages of coco peat—including high porosity, water retention, and moisture content—over soil-based plantation systems.[37]

In terms of vegetative growth, plants in the conventional hydroponic system (Set II) exhibited the greatest performance. This outcome can be attributed to the aeration pump, which enhanced dissolved oxygen availability in the nutrient solution and promoted robust root activity, thereby supporting improved plant stature.[38,39] By contrast, plants in the low-cost bottle-based hydroponic system (Set I) and soil-grown plants (Set III) exhibited shorter stature. While this represented a limitation compared to Set II, the compact growth habit may be advantageous for indoor and vertical farming, where space is restricted. Compact plants that maintain high productivity are desirable in such contexts.[40] Therefore, the establishment of this low-cost hydroponic system using recycled plastic bottles (Set I) represents a promising alternative production strategy for space-constrained urban farming. It supports decentralized food production and urban nutritional security initiatives and can be implemented with minimal infrastructure investment.

Concerning the fruit and yield characteristics, soil-grown plants (Set III) exhibited significantly poorer performance compared to plants cultivated under soilless conditions with hydronic nutrient solutions (Sets I and II). This may be attributed to the lower moisture content and reduced water-holding capacity of soil, which limited nutrient availability in desiccated conditions and ultimately compromised productivity.[41] In contrast, the production of heavier fruits and higher yields in both hydroponic systems underscores the important role of efficient water and nutrient delivery.[42] The balanced availability of essential nutrients also promoted increased biosynthesis of capsaicin in mature *C. annuum* fruits, consistent with earlier reports.[43]

The compromised growth and yield in soil-grown plants may be explained by the higher levels of stress experienced under soil conditions. Elevated peroxide and MDA levels indicated severe oxidative stress, leading to cellular damage.[44] This was further reflected in the rapid depletion of antioxidant enzymes such as SOD and CAT, which play a crucial role in mitigating oxidative damage. Their significantly reduced activities in soil-grown plants further confirm this mechanism.[45] The fruits of *C. annuum* are highly demanded worldwide and widely used in daily cooking. The present study demonstrates that the use of repurposed bottles or other household containers for hydroponics does not compromise either yield (quantitative aspect) or nutritional value (qualitative aspect). Therefore, this approach can be considered a viable and sustainable option for household-level indoor cultivation, as well as for large-scale applications under net or polyhouse conditions.

The present study also underscores the pivotal role of oxidative stress and antioxidant defense in shaping both plant yield and nutritional quality. Yield showed strong positive correlations with the antioxidant enzymes SOD and CAT, indicating that enhanced enzymatic activity supports greater productivity, likely through the mitigation of oxidative damage. In contrast, the significant negative correlation with MDA highlights the detrimental effects of lipid peroxidation on yield. Although the negative

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correlation with H_2O_2 was weak and not statistically significant, it may suggest limited or threshold-based oxidative signaling effects. Moreover, both vitamin C and capsaicin content were positively correlated with SOD and CAT, reinforcing the idea that antioxidant defense not only supports plant growth but also enhances the biosynthesis of nutritionally valuable metabolites. Their inverse relationships with MDA and H_2O_2 further affirm the detrimental impact of oxidative stress on metabolic quality, consistent with earlier studies.[46-48]

Previous reports have also demonstrated the successful use of plastic bottles, beverage containers, and discarded materials in hydroponic vegetable production, employing simple, low-cost designs without reliance on electricity or expensive resources.[49-51] As traditional agriculture faces mounting challenges in addressing food security under climate change, land scarcity, and water shortages, innovative approaches for climate-resilient urban agriculture and cultivation in non-productive areas have gained enormous interest. Such systems are expected to become major contributors to food supply in urban and suburban/peri-urban regions in the near future.[52]

However, one limitation of traditional passive hydroponic systems, such as the wick method or the Kratky method, is that they are primarily suited for leafy greens.[53] These systems are less effective for fruiting crops, which require larger root zones to ensure adequate aeration and nutrient circulation. By contrast, the results of the present study demonstrate that hydroponics using plastic bottles and nutrient solutions achieved yield levels comparable to those obtained with conventional hydroponics. Therefore, beyond its advantages of low cost, space efficiency, and minimal energy requirements, this simple and user-friendly system is also adaptable for underprivileged or urban households. The positive feedback and strong acceptance observed among local communities further highlight its adaptability and potential scalability in the future.

5. Conclusion

The present study evaluated the potential of a low-cost, non-electric, sustainable hydroponic system designed for indoor environments for the production of *C. annuum*. This in-house-built system produced plants with compact, manageable stature and demonstrated both quantitative (fruit yield) and qualitative (vitamin C and capsaicin content) performance comparable to conventional hydroponics systems that rely on electrical inputs. These findings highlight the system's potential as an alternative production model for peri-urban areas and regions facing constraints in arable land availability.

The use of repurposed household materials, such as water and soft drink bottles, not only enhances cost-effectiveness and user accessibility but also promotes recycling of disposable items, directly contributing to Sustainable Developmental Goal (SDG) 12 (responsible consumption and production). The promising yield performance of this system, achieved with minimal resource inputs, aligns with SDG 2 (zero hunger) while also supporting SDG 5 (gender equality) and SDG 8 (decent work and economic growth) by providing opportunities for women and marginalized communities in rural and peri-urban areas. Adoption of this technique could enhance nutritional security at the household level while simultaneously strengthening local economies and promoting gender empowerment. The system can be recommended for large-scale use by women-led self-help groups as a means of advancing gender equality (SDG 5). Overall, this system not only advances sustainable agricultural practices but also contributes to sustainable livelihoods (SDG 8) and circular economies through the use of recycled materials and reliance on locally available inputs.

Ongoing work is focused on evaluating the scalability and the long-term durability of plastic bottles in terms of sustainability. Current experiments include incorporating rainwater harvesting for nutrient solution preparation and foliar spraying to address water conservation, as well as testing a large-scale model using low-cost, locally available containers such as drums. To mitigate environmental concerns regarding plastic degradation, biodegradable or recycled alternatives are also being explored, which will further enhance the ecological footprint of the system.

A forward-looking, integrated research approach will be required for large-scale implementation, focusing on cost-benefit analysis and system scalability. In addition, assessing the applicability of this model to other vegetable crops could broaden its relevance. Collectively, these initiatives could make significant contributions to universal nutritional security in the face of mounting environmental challenges and energy constraints.

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Conflict of interest

The authors declare they have no competing interests.

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Writing–original draft: Somroop Chakravarti, Arnab Sarkar, Anirban Maity, Moumita Gangopadhyay
Writing–review & editing: Moumita Gangopadhyay, G. M. Al Amin

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Data used in this work are available from the corresponding author upon reasonable request.

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Appendix

Table A1. Hydroponic nutrient solution (Hoagland and Arnon[1])

Nutrient	Concentration	Amount
Solution 1		
KH_2PO_4	1 M	1 cc/L nutrient solution
KNO_3	1 M	5 cc/L nutrient solution
$Ca\ (NO_3)_2$	1 M	5 cc/L nutrient solution
$MgSO_4$	1 M	2 cc/L nutrient solution
Supplementary solution a		1 cc/L nutrient solution
H_3BO_3	2.86 g/L water	
$MnCl_2.4H_2O$	1.81 g/L water	
$ZnSO_4.7H_2O$	0.22 g/L water	
$CuSO_4.5H_2O$	0.08 g/L water	
$H_2MoO_4.H_2O$	0.02 g/L water	
Supplementary solution b		1 cc/L nutrient solution
Iron tartrate	0.5%	

Table A2. Seedling vigor index-I of plants after 10 days of germination in different growing media

Growing medium	Seedling vigor index
Soil	509.33 (11.15)^a
Coco peat	736.67 (7.13)^b

Notes: Data presented as the mean (SD); means followed by the same letters are not significantly different (p<0.05).

Table A3. Plant growth parameters and nutritional quality of fruit

Experimental group	Set I	Set II	Set III
Shoot height (cm)	35.57 (1.94)^a	45.73 (1.39)^b	32.70 (3.50)^a
Days required for first flowering	58.65 (2.37)^a	58.35 (1.43)^a	73.65 (3.62)^b
Days required for first fruiting	82.35 (1.57)^a	82.00 (1.62)^a	108.00 (3.16)^b
Days required for complete maturation	112.65 (1.66)^a	113.65 (1.18)^a	134.65 (2.06)^b
Fruit weight (g)	3.16 (0.20)^a	3.20 (0.19)^a	2.07 (0.25)^b
Fruit yield (kg/plant)	1.20 (0.025)^a	1.27 (0.017)^a	0.66 (0.017)^b
Vit. C (mg Ascorbic acid/100 gfw)	109.37 (2.03)^a	108.43 (1.79)^a	84.86 (1.33)^b
Capsaicin (mg/10 gfw)	74.26 (1.75)^a	74.50 (1.75)^a	55.37 (1.91)^b

Notes: Data presented as the mean (SD); means followed by the same letters are not significantly different according to Duncan's multiple range test (p<0.05).

Table A4. Physiological response of plants

Experimental group	H_2O_2 content (µmol/g^{fw})	MDA level (µmol/g^{fw})	SOD (U/g/min)	CAT (U/g/min)
Set I	2.37 (0.079)[a]	2.80 (0.036)[a]	43.00 (0.382)[a]	42.00 (0.034)[a]
Set II	2.47 (0.028)[a]	2.40 (0.032)[a]	45.00 (0.279)[a]	43.33 (0.031)[a]
Set III	6.43 (0.019)[b]	4.60 (0.032)[b]	24.00 (1.009)[b]	22.67 (1.456)[b]

Notes: Data presented as the mean (SD); means followed by the same letters are not significantly different according to Duncan's multiple range test ($p<0.05$).
Abbreviations: CAT: Catalase; H_2O_2: Hydrogen peroxide; MDA: Malondialdehyde; SOD: Superoxide dismutase.

Table A5. Correlation analysis between yield and nutritional performance (Vitamin C and capsaicin) with stress markers (H_2O_2, MDA) and antioxidant enzymes (SOD, CAT)

Parameters	Variables	Correlation coefficient (τ)	*p*-value*
Yield	H_2O_2	−0.208	<0.05
	MDA	−0.604	<0.05
	SOD	0.770	<0.05
	CAT	0.737	<0.05
Vitamin C	H_2O_2	−0.385	<0.05
	MDA	−0.206	<0.05
	SOD	0.567	<0.05
	CAT	0.476	<0.05
Capsaicin	H_2O_2	−0.301	<0.05
	MDA	−0.247	<0.05
	SOD	0.648	<0.05
	CAT	0.553	<0.05

Note: *$p<0.05$ indicates significant statistical correlation.
Abbreviations: CAT: Catalase; H_2O_2: Hydrogen peroxide; MDA: Malondialdehyde; SOD: Superoxide dismutase.

Table A6. Participants' responses (*n*=20) on a 1–5 scale regarding accessibility, technical difficulty, and cost-effectiveness of the low-cost hydroponic system using plastic bottles

Parameter	1	2	3	4	5	Total response
Accessibility	0	0	2	3	15	20
Technical difficulty	12	5	3	0	0	20
Cost-effectiveness	0	0	1	7	12	20

Note: Scale: 1=very low; 5=very high.

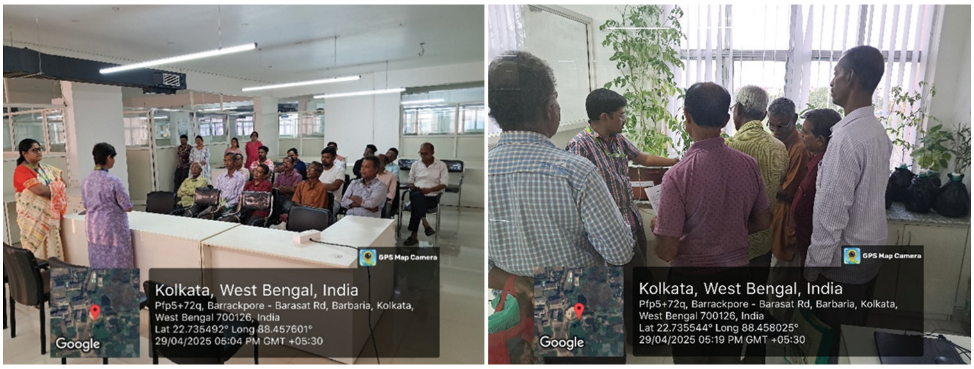

Figure A1. Farmers' training workshop on the low-cost hydroponics setup at Adamas University, Barasat, West Bengal, India

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