



RESEARCH ARTICLE

Enhancing sugar levels in winter-grown watermelon through strategic pruning: Sweetness beyond seasons

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Abstract

The study aimed to enhance the sweetness and fruit quality of winter-grown watermelon by evaluating the effects of distinct pruning methods on growth, yield and physiological and biochemical characteristics. The treatments were control, single stem pruning, double-stem pruning and fruit thinning, which were investigated during 2 consecutive winter seasons under pot and field conditions. Single stem pruning at 35 days after sowing showed the most pronounced improvement among all the tested treatments. This treatment strongly enhanced TSS (9.28 °Brix in pot-grown plants and 8.82 °Brix in field-grown plants) and increased reducing, non-reducing and total sugars compared with the other treatments. Sweetness enhancement is coupled with increased chlorophyll content, enhanced antioxidant enzyme activities and higher accumulation of primary and secondary nutrients in the fruit pulp. Fruit thinning greatly improved external colour; however, single stem pruning was superior in enhancing the internal quality and overall marketability of the fruits. The results indicate that single stem pruning is an effective management practice for increasing sweetness, physiological performance and yield of winter-grown watermelon under off-season production conditions.

Keywords: *Citrullus lanatus*; fruit quality; fruit thinning; pruning; sugar content; sweetness

Introduction

Watermelon, *Citrullus lanatus* (Thunb.) Matsum. & Nakai (Cucurbitaceae) is a warm-season crop valued for its sweet taste and high-water content (~91 %) (1). It is rich in lycopene, citrulline, vitamins, minerals and potassium all of which are involved in maintaining fluid balance in the body, cardiovascular health and reducing the risk of cancer (2–4). India is among the leading producers, cultivating ~110000 ha with a production of 287000 metric tonne (MT) during 2019–2020 (5). This crop has strong economic importance, with exports exceeding 44000 MT in 2022–2023 and market prices ranging from ₹10–25 per kg in summer (6, 7).

Sweetness is a major quality attribute of watermelon and is directly associated with consumer satisfaction and marketability (8). Higher sweetness increases the palatability of fruit, thus increasing its appeal in both local and foreign markets. In this regard, the clarification and improvement of the factors favouring sweetness in watermelon have become a key research agenda for both researchers and watermelon growers.

Watermelon sweetness development faces certain challenges if cultivated during the winter season, which is limited by the relatively low temperature of the season (9). Experimental research has shown that temperature is one of the most important

factors in fruit sugar synthesis, where high temperatures during the day and night promote the synthesis of glucose and fructose (10). Conversely, lower temperatures inhibit photosynthesis and slow down the synthesis of sugars, thus restricting the level of soluble sugars in the fruit (11). Such temperature sensitivity is most noticeable in tropical regions, where watermelons grow in the winter months, possessing significantly lower total soluble solids (TSS) due to limited sugar production at lower temperatures (12). This causes a loss of sweetness in developing fruits, which decreases their marketability (13). Numerous crop management and improvement strategies to increase sugar concentrations in summer-grown watermelons have been reported (14–17), but only limited information is available for winter-grown watermelon, highlighting a serious research gap (9).

In this study, we postulated that pruning techniques, when used on winter-grown watermelon plants, have a significant impact on sugar content by redistributing internal resources that impart sweetness, as pruning can focus resources and energy from vegetative growth to the fruit, increasing sugar buildup and overall sweetness. The main goal of this study was to evaluate the impact of pruning on sweetness and sugar accumulation in winter-grown watermelon to provide empirically based recommendations for quality enhancement during off-season production.

This study was designed to evaluate the effects of different pruning methods on the growth, flowering, yield, sweetness and other related physiological and biochemical characteristics of winter-grown watermelon grown in pots and in field environments. The aims of this study were also to establish an efficient pruning program for off-season watermelon production, which improves fruit quality and commercial yield and which is attained by the combination of intensive sugar profiling and chlorophyll measurements, antioxidant enzyme activity tests and levels of nutrient accumulation.

Materials and Methods

The experiment was conducted over 2 seasons at the Central University of Tamil Nadu (10.80° N, 79.61° E) in a fenced-off experimental area. The mean seasonal air temperature during the winter period (December 2023–February 2024 and December 2024–February 2025) is given in Annexure 1, characterizing mild winter growing conditions. The watermelon plant material used was an icebox-type hybrid, Kalash KSP 1358 Melody and cultivation was performed following the recommended practices described by Yadav et al. (18). They involved proper soil preparation, timing of irrigation and use of fertilisers and pesticides as per standard recommendations.

Four treatments were evaluated under 2 experimental conditions: pot experiments were conducted in a completely randomised design (CRD) with 4 replications during the winter season of 2023, whereas field experiments were carried out in a randomised block design (RBD) with 5 replications during the winter season of 2024. The treatments (Fig. 1) were T1- Control, T2-Single stem pruning (Fig. 1), T3- Double stem pruning (Fig. 2) and T4- Fruit thinning (Fig. 3). The complete details of the treatments administered are mentioned in Supplementary Table 1.

Growth, flowering, yield, biochemical, quality and colour parameters were recorded following standard procedures. Growth attributes, including main axis length, internodal length, number of nodes per plant and stem girth, were measured. Flowering traits were assessed, including days to the first male and female flowers, days to 50 % flowering, number of male and female flowers,

female-to-male flower ratio and flower-to-fruit set ratio. Yield parameters were evaluated, including the number of fruits set, fruits per plant, fruit set percentage, fruit retention percentage and fruit yield per plant, while fruit characteristics were recorded, including fruit length, fruit girth, fruit weight, pulp weight and rind weight. The formulae for calculating the fruit set percentage and fruit retention percentage are as follows:

$$\text{Fruit set percentage (\%)} = \frac{\text{Number of fruits set}}{\text{Total number of female flowers}} \times 100 \quad (\text{Eqn. 1})$$

$$\text{Fruit retention percentage (\%)} = \frac{\text{Number of fruits retained}}{\text{Number of fruits set}} \times 100 \quad (\text{Eqn. 2})$$

Biochemical and quality parameters included chlorophyll a, chlorophyll b and total chlorophyll (19), TSS (20), reducing, non-reducing and total sugars (21) and phosphorus content. Stress-related biochemical parameters, such as proline content (22), peroxidase activity (23) and superoxide dismutase (SOD) activity (24), were also estimated. Colour attributes (L^* , a^* and b^* values) were measured using a digital spectrophotometer (Model TR500, Lovibond, Germany).

The concentration of proline was determined using a standard curve and was expressed in terms of micromoles of proline per gram of fresh leaf weight using the following formula:

$$\text{Proline concentration } (\mu\text{ mol g}^{-1}) = \frac{(\mu\text{g proline/mL} \times \text{mL toluene})}{115.5 \mu\text{g}/\mu\text{mol}} \times \frac{5}{\text{g sample}} \quad (\text{Eqn. 3})$$

Peroxidase activity was calculated using the following formula:

$$\text{Peroxide activity } (\text{U g}^{-1} \text{FW min}^{-1}) = \frac{\Delta A}{\epsilon \cdot l \cdot \text{Protein concentration} \cdot \text{time}} \quad (\text{Eqn. 4})$$

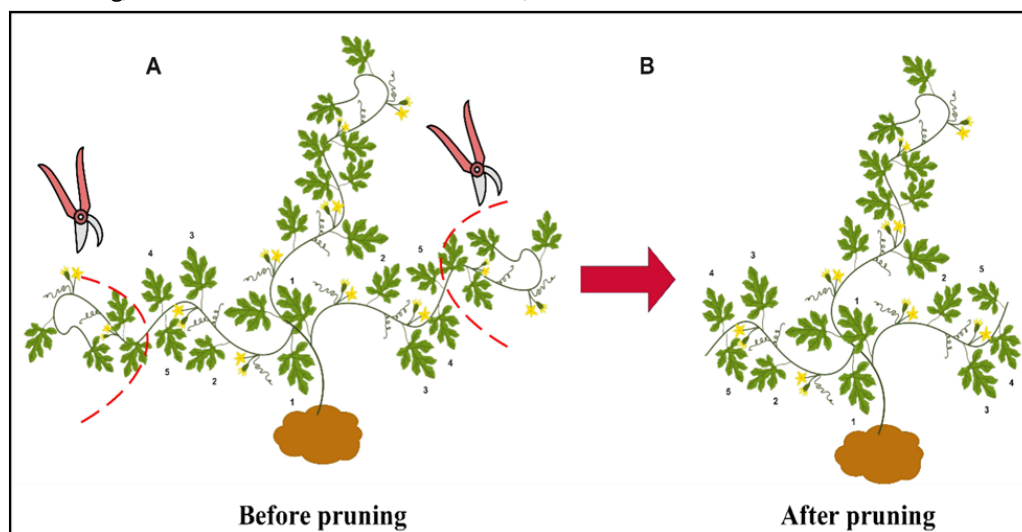


Fig. 1. Single stem pruning (T2) pruning treatment in watermelon (*C. lanatus*) at 35 days after sowing DAS. (A) Diagrammatic representation of the pruning strategy involving the removal of lateral branches beyond the fifth leaf while retaining the integrity of the main stem. Pruning cuts (indicated by red dashed lines) are made to restrict excessive vegetative growth on lateral vines; (B) Post-pruning morphology illustrating the resultant plant architecture, where lateral branches are confined to five leaves, promoting balanced source-sink dynamics.

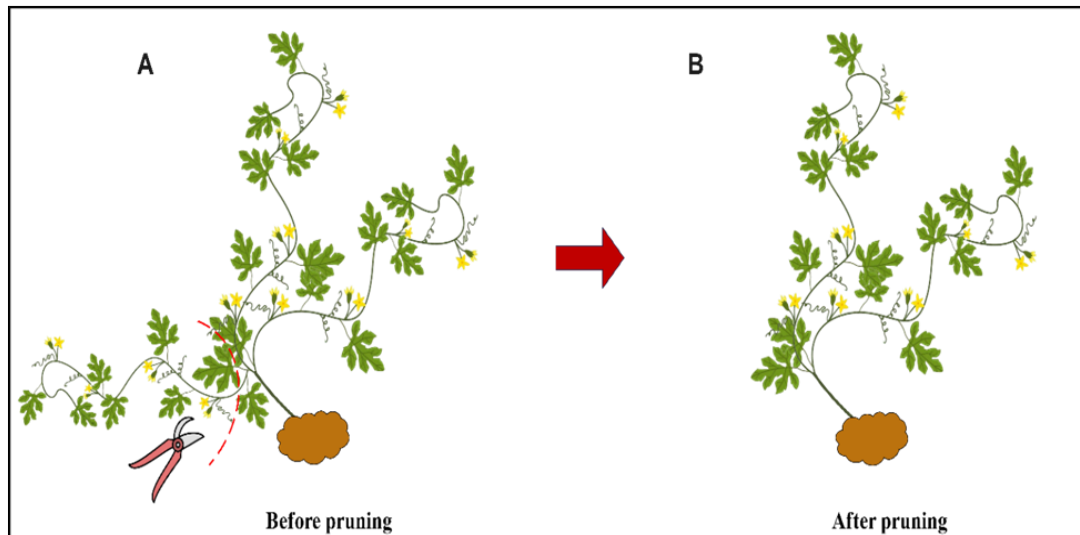


Fig. 2. Double stem pruning (T3) treatment at 35 days after sowing (DAS) in watermelon (*C. lanatus*). (A) Diagram showing the pruning technique where only the main stem and the primary lateral are retained, with all other lateral branches are getting removed, indicated by red dashed lines. This selective pruning ensures the plant maintains two primary stems, enhancing controlled growth; (B) Post-pruning morphology of the plant after the removal of excess lateral branches.

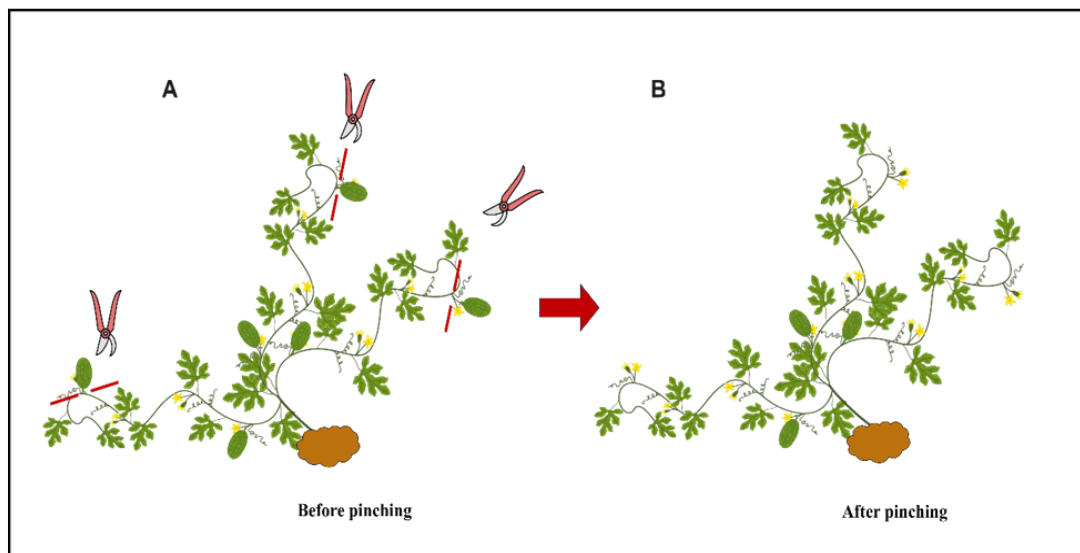


Fig. 3. Fruit thinning (T4) treatment in watermelon (*C. lanatus*) applied at the 3 cm fruit diameter stage. (A) Schematic representation of fruit thinning where all developing fruits are removed except for the three closest to the main stem (highlighted by red dashed lines). This targeted removal is conducted using manual pinching or pruning shears to eliminate distal fruits; (B) Post-thinning vine morphology, showing retention of only three proximal fruits to enhance resource allocation and support optimal fruit development.

where,

ΔA = Final absorbance - Initial absorbance

ϵ = Molar extinction coefficient of pyrogallol at 420 nm

l = Path length of cuvette (typically 1 cm)

Protein concentration =

Protein content of enzyme extract(mg/mL)

Time = Duration of reaction measurement (usually 5 min)

Statistical analysis was performed separately for the 2 experiments using a one-way analysis of variance (ANOVA). The experimental data were analysed using RAISINS, an online statistical platform integrating R and Python-based analytical tools for agricultural research. Treatment means were compared using the least significant difference (LSD) test at the 5 % probability level ($p=0.05$).

Results

Effect of various pruning techniques on growth of watermelon

Pruning practices significantly influenced the vegetative growth characteristics of watermelon in pot and field settings ($p \leq 0.05$) (Supplementary Table 2). The single stem pruning treatment (T2) persistently increased the main axis length, internodal length, number of nodes per plant and stem girth compared to the control and other pruning regimes and proved to be better in vine growth and plant structure. Intermediate responses were caused by double-stem pruning (T3) but not by fruit thinning (T4). Comprehensively, single stem pruning was the most effective method for vegetative growth under the examined growing conditions. For further clarification, refer to Supplementary Table 1.

Effect of various pruning techniques on flowering and reproduction of watermelon

Pruning treatments had a significant effect on the flowering of watermelon under pot and field conditions ($p \leq 0.05$) (Supplementary Table 3). Single stem pruning (T2) enhanced male

and female flowering and shortened the time to 50 % flowering relative to the control, which is beneficial for reproductive earliness. Intermediate development of flowering was achieved when the plants were pruned with double-stem (T3), but a delay in flowering was observed when the plants were pruned with thinning (T4).

The treatments also positively influenced reproductive characteristics. Single stem pruning enhanced the female flower count, female-to-male flower ratio and female-to-fruit set ratio, signifying greater reproductive efficiency. Other management practices, such as double-stem pruning and fruit thinning, also enhanced the flowers-to-fruit set ratio, especially under pot conditions, but were less effective than single stem pruning on the overall reproductive performance. The complete numerical data for these results are provided in Supplementary Table 3.

Effect of various pruning techniques on yield and fruit characteristics and of watermelon

Pruning treatments significantly influenced the fruit set, fruit retention and yield attributes of watermelon ($p \leq 0.05$) under both pot and field conditions (Tables 1 and 2). Single stem pruning (T2) was the most effective intervention for maximising final yield because it increased the number of fruits retained and the number of fruits retained per plant, total fruit yield per plant and reduced fruit abscission. T3 was most associated with a higher initial fruit set, but this was not always transferred into a better final yield. Fruit thinning (T4) enhanced the percentage fruit set, particularly under pot conditions, but was not as effective as when using field conditions.

Pruning treatments also significantly affected the physical characteristics of the fruit. Single stem pruning produced significantly longer and heavier fruits than the control (Fig. 4), which directly contributed to enhanced yield attributes in the former. Double-stem pruning resulted in intermediate fruit size and weight, whereas fruit thinning showed no consistent or significant improvement in fruit dimensions compared with pruning treatments.

Yield-related parameters were also significantly enhanced by single stem pruning than the control. Treatment T2 had much higher values of pulp weight and rind weight between the 2 experimental conditions compared to the control which had the lowest values at all times. Although, in the case of double-stem pruning, there were also statistically significant increases in specific yield traits relative to the control, the increase was significantly less than that with single stem pruning. In general, single stem pruning was statistically better for increasing fruit retention, fruit size and total yield of watermelon under both pot and field conditions.

Effect of various pruning techniques on quality parameters of watermelon

The fruit quality attributes of watermelon were significantly influenced by the pruning treatments under both pot and field conditions ($p \leq 0.05$) (Table 3, Fig. 4). Single stem pruning (T2) consistently enhanced fruit quality, resulting in higher TSS (Fig. 5) and increased accumulation of reducing, non-reducing and total sugars (Fig. 5) compared to the control. These improvements indicate superior sweetness and carbohydrate partitioning in T2. Double-stem pruning (T3) also improved sugar-related quality

Table 1. Effect of pruning and fruit thinning treatments on the yield of watermelon

Treatment	No. of fruits set		Fruits per plant		Fruit set percentage (%)		Fruit retention percentage (%)		Fruit yield per plant (kg)	
	Field	Pot	Field	Pot	Field	Pot	Field	Pot	Field	Pot
T1 (Control)	2.72 ± 0.05 ^c	2.40 ± 0.13 ^c	1.48 ± 0.02 ^c	1.33 ± 0.13 ^c	68.83 ± 0.22 ^b	69.41 ± 12.96 ^b	54.31 ± 0.88 ^c	55.81 ± 3.60 ^b	0.10 ± 0.01 ^c	0.11 ± 0.01 ^c
T2 (Single stem pruning)	3.18 ± 0.11 ^{ab}	2.88 ± 0.12 ^b	2.03 ± 0.05 ^a	1.78 ± 0.03 ^a	70.53 ± 4.28 ^b	73.13 ± 1.93 ^b	63.59 ± 2.87 ^a	61.96 ± 3.09 ^a	0.12 ± 0.01 ^b	0.14 ± 0.01 ^a
T3 (Double stem pruning)	3.27 ± 0.13 ^a	3.56 ± 0.21 ^a	1.94 ± 0.06 ^b	1.71 ± 0.01 ^a	74.50 ± 5.00 ^b	85.84 ± 4.42 ^a	57.72 ± 3.54 ^b	48.80 ± 2.53 ^c	0.12 ± 0.01 ^b	0.12 ± 0.00 ^b
T4 (Fruit thinning)	3.05 ± 0.07 ^b	2.99 ± 0.08 ^b	1.49 ± 0.04 ^c	1.50 ± 0.02 ^b	81.65 ± 4.00 ^a	86.41 ± 3.36 ^a	49.47 ± 1.28 ^d	49.95 ± 1.73 ^c	0.15 ± 0.01 ^a	0.11 ± 0.00 ^c
CD	0.13	0.22	0.05	0.1	5.8	10.96	3.16	4.35	0.01	0.01

Cell values are mean ± SD; Different superscript letters (a, b, c) within a column indicate significant differences between treatments according to LSD at $p < 0.05$. Treatments with the same letter grouping are not significantly different.

Table 2. Effect of pruning and fruit thinning treatments on fruit characteristics of watermelon

Treatment	Fruit length (cm)		Fruit girth (cm)		Fruit weight (kg)		Pulp weight (kg)		Rind weight (kg)	
	Field	Pot	Field	Pot	Field	Pot	Field	Pot	Field	Pot
T1 (Control)	33.38 ± 0.06 ^b	33.38 ± 0.06 ^b	39.28 ± 0.08 ^b	40.61 ± 0.12 ^b	51.92 ± 0.73 ^a	51.58 ± 0.55 ^a	39.14 ± 2.99 ^a	31.30 ± 1.20 ^a	3.95 ± 0.07 ^b	3.51 ± 0.42 ^b
T2 (Single stem pruning)	30.28 ± 0.06 ^d	30.08 ± 0.09 ^d	36.90 ± 0.06 ^d	36.81 ± 0.07 ^d	39.91 ± 0.15 ^d	39.88 ± 0.45 ^d	36.43 ± 2.19 ^{ab}	28.80 ± 0.39 ^b	4.52 ± 0.26 ^a	3.98 ± 0.26 ^a
T3 (Double stem pruning)	31.22 ± 0.58 ^c	30.35 ± 0.07 ^c	37.27 ± 0.07 ^c	37.24 ± 0.08 ^c	41.98 ± 0.19 ^c	41.17 ± 0.17 ^c	35.59 ± 1.84 ^b	30.70 ± 1.38 ^a	4.41 ± 0.26 ^a	3.83 ± 0.23 ^{ab}
T4 (Fruit thinning)	34.31 ± 0.07 ^a	34.30 ± 0.08 ^a	39.86 ± 0.08 ^a	41.26 ± 0.14 ^a	43.08 ± 0.19 ^b	42.44 ± 0.18 ^b	24.67 ± 1.37 ^c	31.16 ± 0.58 ^a	3.74 ± 0.14 ^b	3.44 ± 0.08 ^b
CD	0.39	0.11	0.02	0.16	0.51	0.58	3.24	1.5	0.29	0.43

Cell values are mean ± SD; Different superscript letters (a, b, c) within a column indicate significant differences between treatments according to LSD at $p < 0.05$. Treatments with the same letter grouping are not significantly different.

Table 3. Effect of pruning and fruit thinning treatments on soluble solids and sugar content in watermelon

Treatment	Total soluble solids ($^{\circ}\text{Bx}$)		Reducing sugars (%)		Non-reducing sugars (%)		Total sugars (%)	
	Field	Pot	Field	Pot	Field	Pot	Field	Pot
T1 (Control)	7.92 \pm 0.08 ^{bc}	7.17 \pm 0.22 ^d	2.65 \pm 0.28 ^c	2.54 \pm 0.23 ^c	1.68 \pm 0.07 ^d	1.57 \pm 0.07 ^c	4.33 \pm 0.28 ^c	4.11 \pm 0.19 ^c
T2 (Single stem pruning)	8.82 \pm 0.15 ^a	9.28 \pm 0.05 ^a	3.66 \pm 0.24 ^a	3.45 \pm 0.23 ^a	2.68 \pm 0.09 ^a	2.47 \pm 0.09 ^a	5.55 \pm 0.55 ^a	5.91 \pm 0.26 ^a
T3 (Double stem pruning)	8.09 \pm 0.19 ^b	8.83 \pm 0.10 ^b	3.47 \pm 0.18 ^a	3.27 \pm 0.15 ^a	2.56 \pm 0.09 ^b	2.36 \pm 0.09 ^{ab}	5.35 \pm 0.51 ^a	5.63 \pm 0.12 ^a
T4 (Fruit thinning)	7.88 \pm 0.08 ^c	7.73 \pm 0.01 ^c	3.06 \pm 0.15 ^b	2.89 \pm 0.11 ^b	2.48 \pm 0.10 ^c	2.30 \pm 0.11 ^b	5.00 \pm 0.33 ^b	5.19 \pm 0.21 ^b
CD	0.17	0.19	0.27	0.29	0.05	0.14	0.33	0.31

Cell values are mean \pm SD; Different superscript letters (a, b, c) within a column indicate significant differences between treatments according to LSD at $p < 0.05$. Treatments with the same letter grouping are not significantly different.

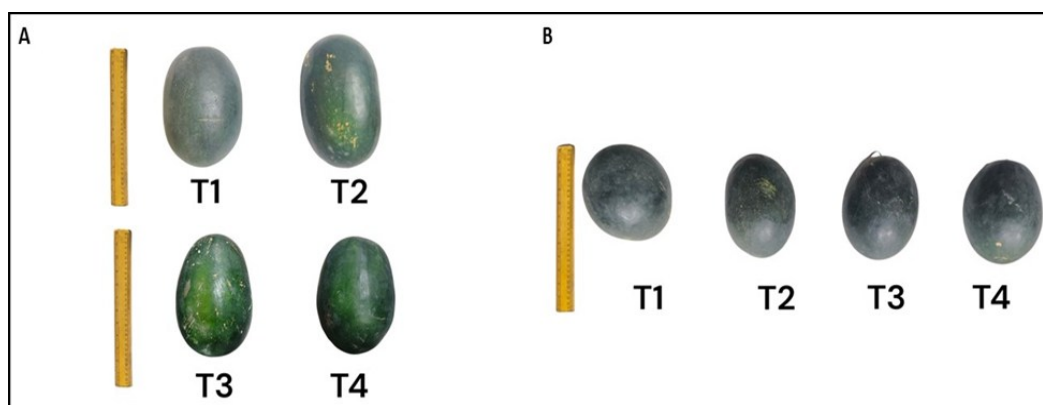


Fig. 4. Effect of different pruning treatments on fruit size and morphology in watermelon. (A) Fruits harvested from field-grown plants under treatments T1 (Control), T2 (Single stem pruning), T3 (Double stem pruning) and T4 (Fruit thinning); (B) Fruits harvested from pot-grown plants under the same treatments (T1-T4). A ruler scale is included for size reference.

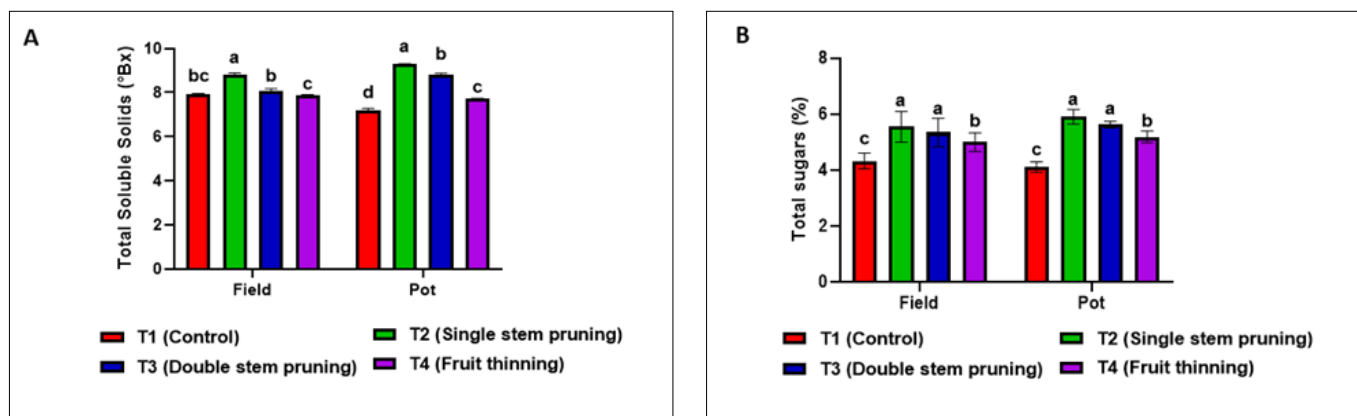


Fig. 5. Effect of various pruning techniques on sugar content in watermelon. (A) Total soluble solids ($^{\circ}\text{Bx}$); (B) Total sugars (%) across different treatments (T1-T4) in both pot and field conditions.

parameters, particularly total sugars; however, the response was consistently lower than that observed under single stem pruning. Fruit thinning (T4) produced moderate improvements in sugar content; however, its effect was less pronounced and inconsistent compared that with of pruning treatments. Overall, single stem pruning proved to be the most effective method for enhancing the sweetness and overall quality of watermelon fruits across growing conditions.

Effect of various pruning techniques on biochemical parameters of watermelon

The treatments of pruning and fruit thinning showed a statistically significant effect ($p \leq 0.05$) on the stress-related biochemical parameters of watermelon, such as proline concentration, peroxidase activity and SOD activity when compared in pot and field conditions (Supplementary Table 4). The best values of all

3 parameters were obtained using the single stem pruning treatment (T2) which means that the stress tolerance and antioxidant capacity were significantly improved compared to the control (Fig. 6).

The levels of proline accumulation and enzyme activities with double-stem pruning (T3) were very high compared to the control, but they were still very low compared to the levels with single stem pruning. Fruit thinning (T4) resulted in moderate changes in the biochemical parameters and was much better than the control but much worse than both T2 and T3 in all of the measured parameters. The control treatment always had the lowest values of proline accumulation and antioxidant enzyme activity. The overall significance of the statistical outcomes regarding the various treatments underscores the commendable efficacy of single stem pruning in improving the biochemical reactions of watermelon plants under stress conditions.

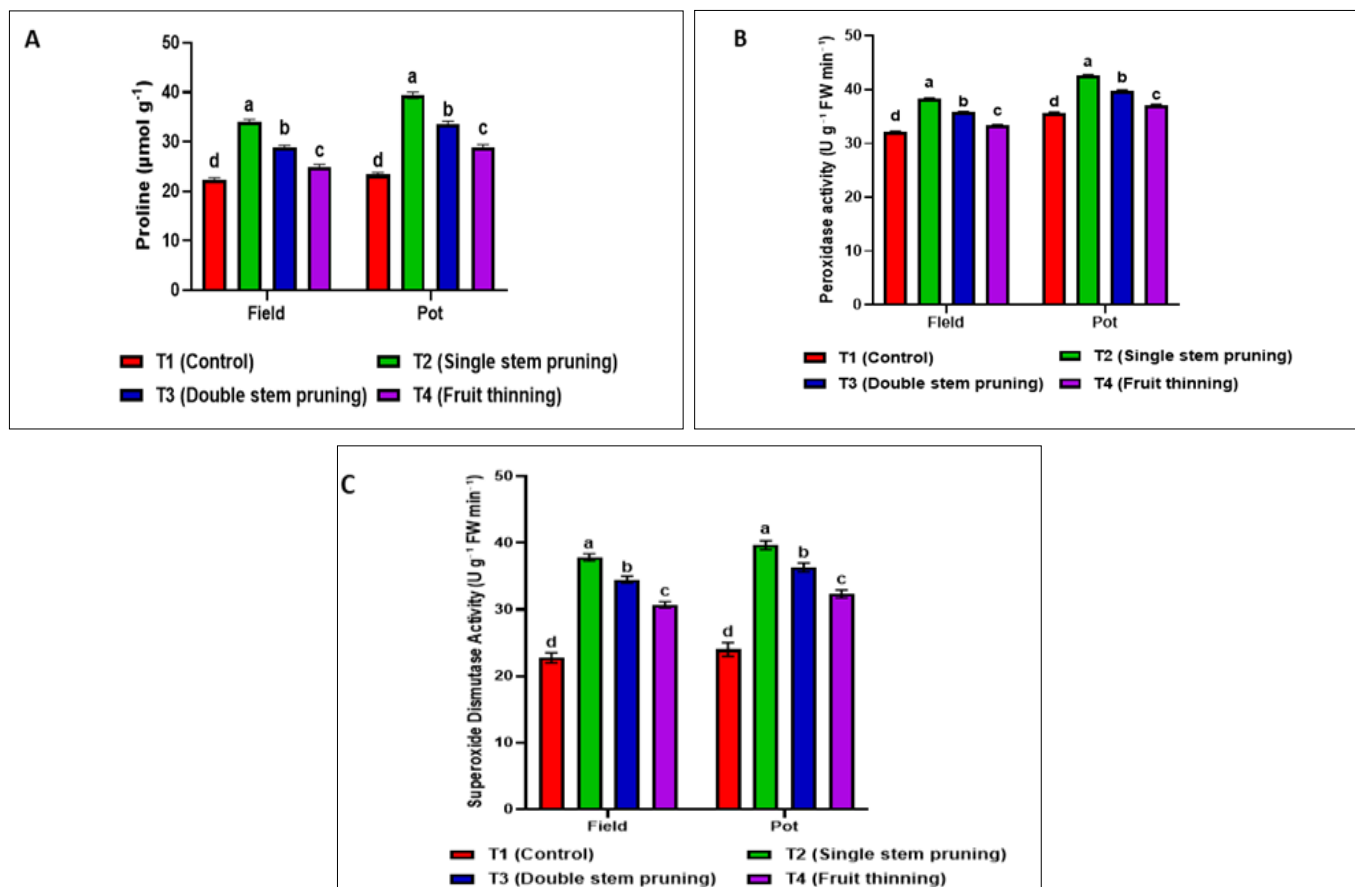


Fig. 6. Effect of various pruning techniques on biochemical parameters in watermelon. A. Proline content; B. Peroxidase activity; C. Superoxide dismutase activity.

Pruning regimes also had a significant impact on chlorophyll concentrations (Supplementary Table 4). The highest chlorophyll a, chlorophyll b and total chlorophyll concentrations were obtained with single stem pruning (T2) under both cultivation conditions which reflects better photosynthetic capacity. The chlorophyll values of double stem pruning were intermediate, but fruit thinning led to less chlorophyll accumulation than other pruning modalities. The results showed that single stem pruning was the most effective method for enhancing the biochemical stability and photosynthetic efficiency of watermelon under the experimental conditions.

Effect of various pruning techniques on nutrient composition of watermelon fruit pulp

The pruning treatments had a significant effect on the amount of nutrients ($p \leq 0.05$) accumulated in the watermelon fruit pulp under both pot and field conditions (Table 4). Single stem pruning (T2)

resulted in significantly higher primary nutrient concentrations, indicating improved nutrient uptake and partitioning compared with the control. T3 (double-stem pruning) yielded an intermediate enhancement in these nutrients and T4 (fruit thinning) yielded a relative decrease, especially with respect to nitrogen and phosphorus, although both were significantly greater than the control in terms of potassium content.

Pruning practices also enhanced the secondary nutrient composition. Single stem pruning (T2) produced sustained increases in the Ca and Mg levels in the fruit pulp, which is a sign of improved mineral nutrition and fruit quality. The moderately high responses to Ca and Mg levels following double-stem pruning and fruit thinning when compared to the control were not as effective as those following single stem pruning. Together, single stem pruning proved to be the most useful for increasing the macro and secondary nutrient content of watermelon fruit pulp under varying growing conditions.

Table 4. Effect of pruning treatments on nutrient composition of watermelon

Treatment	Nitrogen content (mg g ⁻¹)		Phosphorus content (mg g ⁻¹)		Potassium content (mg g ⁻¹)		Calcium content (mg g ⁻¹)		Magnesium content (mg g ⁻¹)	
	Field	Pot	Field	Pot	Field	Pot	Field	Pot	Field	Pot
T1 (Control)	8.39 ± 0.04 ^d	8.26 ± 0.45 ^d	0.04 ± 0.00 ^b	0.04 ± 0.00 ^b	0.83 ± 0.08 ^c	0.82 ± 0.03 ^d	0.06 ± 0.01 ^c	0.05 ± 0.00 ^c	0.07 ± 0.01 ^c	0.05 ± 0.01 ^c
T2 (Single stem pruning)	13.17 ± 0.09 ^b	12.47 ± 0.06 ^a	0.11 ± 0.01 ^a	0.09 ± 0.01 ^a	1.17 ± 0.12 ^a	1.11 ± 0.08 ^a	0.09 ± 0.01 ^a	0.08 ± 0.01 ^a	0.09 ± 0.01 ^a	0.10 ± 0.01 ^a
T3 (Double stem pruning)	13.78 ± 0.17 ^a	11.47 ± 0.06 ^b	0.10 ± 0.01 ^a	0.09 ± 0.01 ^a	1.05 ± 0.06 ^b	1.04 ± 0.01 ^b	0.08 ± 0.01 ^b	0.07 ± 0.01 ^b	0.08 ± 0.00 ^b	0.08 ± 0.00 ^b
T4 (Fruit thinning)	12.27 ± 0.09 ^c	11.07 ± 0.05 ^c	0.05 ± 0.00 ^b	0.04 ± 0.01 ^b	0.98 ± 0.04 ^b	0.93 ± 0.01 ^c	0.08 ± 0.00 ^b	0.07 ± 0.01 ^{ab}	0.08 ± 0.00 ^b	0.07 ± 0.01 ^b
CD	0.15	0.36	0.01	0.01	0.12	0.06	0.01	0.01	0.01	0.01

Cell values are mean ± SD; Different superscript letters (a, b, c) within a column indicate significant differences between treatments according to LSD at $p < 0.05$. Treatments with the same letter grouping are not significantly different.

Effect of various pruning techniques on colour quality parameters of watermelon

The influence of different pruning methods on the colour quality parameters of watermelon (Fig. 7), namely L^* , a^* and b^* values, showed statistically significant differences among treatments ($p \leq 0.05$).

Regarding the L^* value of lightness, the control treatment (T1) had the lowest readings in both pot and field conditions, indicating that the flesh colour was darker. The pruning and thinning treatments (T2, T3 and T4) exhibited significantly higher L^* values than the control, with no significant difference between T2, T3 and T4 within either experimental condition. The a^* -value (redness) was also significantly affected ($p \leq 0.05$) by the pruning treatments. The lowest a^* values were found in the control treatment, with all forms of pruning and thinning increasing the degree of redness. The maximum a^* value was obtained with fruit thinning (T4) which was statistically identical to single stem pruning (T2) but much larger than double-stem pruning (T3) in pot and field conditions. This trend was also observed for the b^* value (yellowness/vibrancy). The control treatment resulted in the lowest b^* values and all the pruning treatments significantly increased the b^* values. The highest b^* values were obtained with T4, whereas the single stem pruning (T2) was statistically equal to T4 and superior to the alternative (T3) in both cases. Although T4 showed the highest numbers, single stem pruning (T2) was as effective in improving the overall quality of pulp colour (L^* , a^* and b^*).

Discussion

Pruning of lateral branches is known to redirect assimilates toward the main stem, improving vine elongation and stem thickening by reducing competition among the growing points (25, 26). Defoliation of secondary branches has been associated with earlier flowering and lower node appearance due to a better distribution

of resources toward the main axis and developing floral meristems (27). Among the pruning strategies evaluated in the present study, single stem pruning (T2) was the most effective, aligning with earlier findings that winter-grown watermelons respond strongly to restricted branching (28). This treatment likely optimises the endogenous hormonal balance, particularly auxin-cytokinin dynamics, which regulate vegetative growth and reproductive development (29).

The improved growth and yield under T2 can be attributed to enhanced source-sink relationships. Restricting fruiting sites to the primary stem concentrates assimilate flow toward fewer developing fruits, resulting in increased fruit size, pulp weight and yield. Similar improvements in fruit mass and plant vigour under selective pruning have been previously reported (30). The more open canopy architecture under T2 likely enhanced light penetration and air movement, supporting better photosynthetic efficiency and reducing shading-related losses (31, 32).

The higher soluble solids and sugar content under T2 further support the advantage of optimising assimilate flow. By reducing competing sinks, single stem pruning favours carbohydrate accumulation in fruits, which contributes to sweetness and improved internal quality (33, 34).

Physiologically, T2 induced moderate stress responses that may have strengthened the metabolic efficiency. The controlled removal of lateral shoots at 35 DAS appeared to trigger a higher accumulation of protective metabolites, including proline, consistent with the literature showing that mild stress enhances osmotic adjustment and antioxidant responses (35, 36). Elevated peroxidase and SOD activity in T2 compared to that in T1 and T3 suggests enhanced ROS detoxification capacity (37–41), which can improve physiological stability. This controlled stress effect was less apparent in the fruit-thinning treatment (T4), which altered the sink load without directly inducing stress signalling pathways.

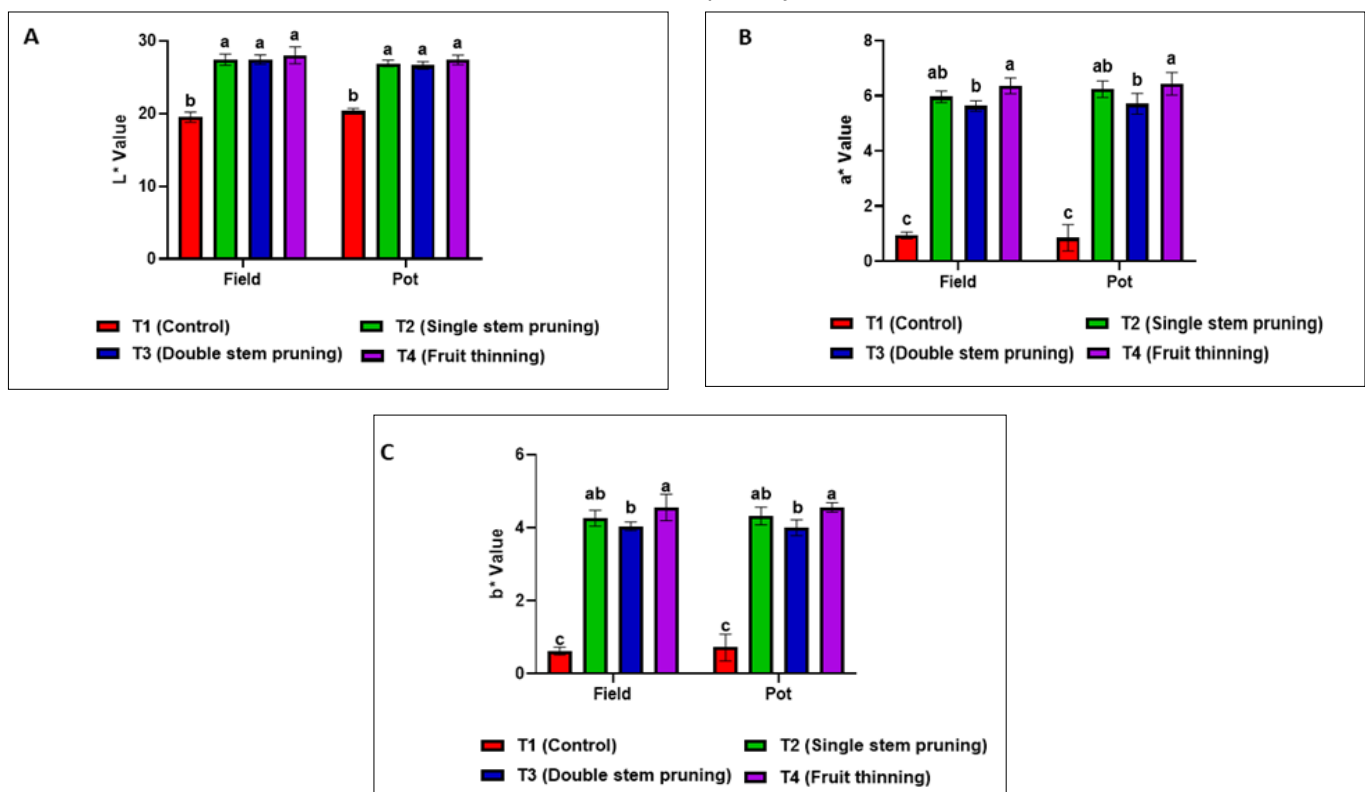


Fig. 7. Effect of pruning techniques on fruit colour intensity levels (L^* , a^* and b^* values).

Photosynthetic attributes also benefitted from T2. Increased chlorophyll a, b and total chlorophyll imply better canopy efficiency and chloroplast development. Reduced shading and more efficient allocation of carbon and nitrogen to the main stem may have facilitated higher Rubisco activity and photosynthetic capacity (42, 43). Hormonal shifts induced by pruning, particularly changes in auxin-cytokinin balance, may further encourage chloroplast biogenesis (44). Excessive branching in T1 limits light distribution, whereas T3 does not sufficiently reduce the vegetative competition. T4 influences fruit load but does not modify the vegetative structure to enhance photosynthesis, similar to observations in earlier studies (45).

Nutrient accumulation patterns also indicated a clear advantage for T2. Higher N, P and K concentrations were likely due to improved nutrient uptake efficiency and reduced sink competition. Similar effects of pruning on nutrient mobilisation have been documented for other fruit crops (46, 47). Increased Ca and Mg deposition suggests strengthened xylem transport and improved hydraulic conductance, which supports fruit development and structural integrity (48–50).

Colour development was highest under T4, likely due to the reduced fruit load and enhanced sunlight exposure, which accelerated pigment biosynthesis. Although T2 did not match T4 in colour intensity, it maintained commercially acceptable colouration while providing superior yield, sweetness and physiological performance.

Taken together, single stem pruning (T2) emerged as the most effective strategy for improving yield, sweetness, nutrient assimilation, canopy efficiency and overall plant performance. These integrated physiological responses support the conclusion that optimizing plant architecture through strategic pruning enhances the source-sink balance and improves fruit quality in watermelon grown under winter conditions.

Conclusion

Single stem pruning (T2) has been found to greatly enhance vegetative, fruiting and fruit quality in winter-grown watermelon by increasing the percentage of assimilates allocated to reproductive development. This treatment enhances the ratio of female to male flowers, fruit set and fruit retention, resulting in larger and sweeter fruits with high aggregate soluble solids (TSS) and sugar. Stress tolerance and physiological vigour were further enhanced by increased nutrient deposition and antioxidant activity over T2. Although systematic fruit thinning (T4) resulted in positive outcomes in terms of pulp colour and brightness, T2 was more effective in increasing overall fruit size, sweetness and yield. Therefore, single stem pruning is an effective management practice for enhancing winter watermelon yield and its marketability. Future research should test this pruning methodology on various cultivars and agroclimatic settings to fine-tune the recommendations for large-scale application and sustainability.

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Authors' contributions

AAS designed and conducted the experiments, collected and analysed the data and prepared the initial draft of the manuscript. IAP assisted in experimental execution, sample management and laboratory analyses. ARK provided technical guidance, contributed to scientific interpretation and reviewed the manuscript. SK supported methodological planning and contributed to manuscript refinement. SS conceptualised and framed the research problem, supervised all stages of the study, guided data interpretation and reviewed the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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