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Effects of Hydrocooling Duration on the Postharvest Quality of Tomato (*Solanum lycopersicum* L.)

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ABSTRACT

Tomato (*Solanum lycopersicum* L.) deteriorates rapidly when field heat is not removed after harvest. This study evaluated hydrocooling durations of 0, 5, 10, 15, 20, and 25 min in water maintained at 16 °C, followed by 14 days of ambient storage. A single-factor completely randomized design with four replications per treatment was used. Weight loss, firmness, total soluble solids, vitamin C, carotenoid content, colour, and texture were evaluated. On day 14, the 15–25 min treatments produced lower weight loss, greater firmness, lower total soluble solids, and higher vitamin C than the untreated control. They also delayed carotenoid accumulation, colour development, and softening. Fifteen minutes produced quality outcomes comparable to the longer treatments with a shorter immersion time. Complete reporting of pulp-temperature reduction, repeated-measures analysis, water sanitation, and analytical methods is required before the protocol can be independently reproduced.

Keywords: ambient storage, field-heat removal, postharvest physiology, precooling, shelf life

INTRODUCTION

Tomato (Solanum lycopersicum L.) is an important horticultural commodity that contributes to human nutritional intake. It is consumed extensively in fresh and processed forms and provides vitamin C, carotenoids—particularly lycopene—and several other antioxidant compounds (Ali *et al*., 2021).

Strong consumer demand gives tomatoes considerable economic value and makes postharvest quality management essential for retaining their nutritional and commercial properties until they reach the market (Li *et al*., 2025). Tomato quality is commonly characterized by firmness, colour, soluble-solids concentration, sugars, organic acids, vitamin C, and lycopene, all of which influence flavour and consumer acceptance (Cheng *et al*., 2020).

As a climacteric fruit, tomato continues to ripen after harvest and undergoes a rise in respiration and ethylene production. Without suitable handling, this activity leads to rapid softening, weight loss, premature colour development, and an overall decline in marketable quality (Sutanto *et al*., 2025). Residual field heat further accelerates

metabolism and shortens storage life. In Indonesia, tomatoes are commonly stored under ambient conditions without a preliminary cooling treatment, so the fruit may ripen and decay before reaching consumers. A practical method for promptly lowering internal fruit temperature is therefore needed (Restian *et al*., 2022; Li *et al*., 2025).

Pre-cooling removes field heat shortly after harvest and can suppress respiration, limit transpiration-related water loss, and reduce susceptibility to microbial deterioration (Lengkey *et al*., 2023; Ridwan *et al*., 2022). Hydrocooling is a simple form of pre-cooling in which cold water rapidly absorbs heat from the harvested commodity. The method is relatively efficient, inexpensive, and technically accessible (Ngadiono *et al*., 2019). By lowering tissue temperature, hydrocooling moderates postharvest metabolism and helps retain fruit quality during subsequent storage (Makule & Dimoso, 2022). Previous studies have associated pre-cooling with reduced weight loss, greater firmness, delayed colour development, and improved vitamin C retention (Gomez *et al*., 2023; Ali *et al*., 2025; Naibaho *et al*., 2025).

The effectiveness of hydrocooling, however, depends strongly on immersion time. Insufficient exposure may leave substantial field heat within the fruit, whereas excessive cooling may increase the risk of physiological injury or chilling-related damage (Vigneault *et al*., 2000; Gomez *et al*., 2023).

De Chiara *et al*. (2024) emphasized that pre-cooling protocols should account for the sensitivity of plant tissues to both water contact and low temperature. Selecting an appropriate duration is therefore central to achieving sufficient heat removal without adversely affecting tomato quality.

Most earlier pre-cooling studies have focused on refrigerated storage or treatments combined with other postharvest technologies. Information comparing different hydrocooling durations followed by ambient storage remains limited, even though room-temperature distribution and marketing are still common in Indonesia. This study therefore evaluated the effects of several hydrocooling durations on the physical, chemical, and sensory quality of tomatoes held at room temperature. The findings were expected to provide a scientific basis for recommending an effective and practical treatment duration.

MATERIALS AND METHODS

Grade A Mustafi tomatoes were obtained from growers in Sangiang Village, Banjaran Subdistrict, Majalengka Regency. Fruit without visible pest infestation or disease symptoms and showing a green-to-orange stage of maturity were selected as experimental samples.

The experiment was carried out in April 2026 in Sindanghaji Village, Palasah Subdistrict, Majalengka Regency, and at the Physiology Laboratory of Swadaya Gunung Jati University, Cirebon. Materials included Mustafi tomatoes, distilled water, ice for the cooling medium, ascorbic acid, iodine (I_2) solution, and starch indicator. A cooler box, basins, plastic containers, analytical balance, thermometer, stopwatch, penetrometer, handheld refractometer, and UV–Vis spectrophotometer were used.

A single-factor completely randomized design was used with hydrocooling duration at six levels: 0, 5, 10, 15, 20, and 25 min. Water temperature was maintained at 16 °C. Before submission, the authors should report initial and final pulp temperatures, cooling rate, water-to-fruit ratio, agitation, temperature tolerance, and the method used to verify uniform cooling.

Each treatment was replicated four times, with 10 tomatoes per experimental unit (240 fruit

in total). Storage conditions ranged from 25 to 28 °C and 70% to 80% relative humidity. The final submission should define the randomisation procedure, biological unit, allocation of fruit to destructive analyses, sensor accuracy, logging frequency, and use of repeated versus independent samples.

Hydrocooling and Storage Procedure

The experimental sequence consisted of harvesting, sorting, transport, hydrocooling, draining, storage, observation, and laboratory analysis. Tomatoes assigned to H1–H5 were fully immersed in water for the prescribed duration. Ice was added as necessary to maintain the medium at 16 °C.

Independent containers were used for treatments and the control remained unimmersed. After hydrocooling, fruit were drained, air-dried, and stored for 14 days in a ventilated area protected from direct sunlight. The water source, sanitation treatment, replacement schedule, microbial controls, drying conditions, and independence of replicate water baths must be reported.

Observation Parameters

Weight Loss

Weight was recorded with a digital balance on storage days 1, 5, 9, and 14. Weight loss was expressed as the percentage reduction from the initial mass (W_0) to the mass measured at each observation (W_t), using the following equation:

$$\textbf{Weight Loss} = \frac{\boldsymbol{W0 - Wt}}{\boldsymbol{W0}} \boldsymbol{x}\ \mathbf{100\%}$$

Notes:
W0 = Weight on day 0 (g)
Wt = Weight on day n (g)

Firmness

Firmness was measured on days 1, 5, 9, and 14 using a penetrometer at the upper, middle, and lower portions of each tomato. The final submission must report the instrument model, probe geometry, calibration, penetration depth and speed, number of fruit, destructive-sampling procedure, and verified unit, preferably in SI units.

Total Soluble Solids (°Brix)

TSS was determined on days 1, 5, 9, and 14 with an Atago PR-201α digital refractometer covering 0–60 °Brix. Before measurement, the instrument was calibrated to 0 °Brix with distilled water. Tomatoes representing each treatment were crushed, and several drops of the extracted juice were placed on the clean prism. The result shown on the display was recorded in °Brix.

Vitamin C

Vitamin C was measured on days 1 and 14 by iodometric titration with 0.01 N iodine and starch indicator and expressed as mg 100 g^{-1}. The final submission must define sample mass, extraction and filtration, iodine equivalence constant, endpoint, dilution factor, biological and technical replicates, and the complete calculation equation.

$$\boldsymbol{Vitamin\ C\ (mg/100g)} = \frac{\boldsymbol{VI_2 \times KI \times FP}}{\boldsymbol{m}} \times \mathbf{100}$$

Notes:
VI_2 = volume of iodine used (mL)
KI= iodine calibration
FP = dilution factor
m = sample mass (g)

Carotenoids

Carotenoid content was measured on days 1 and 14 using UV–Vis spectrophotometry. The method must be completed with sample mass, extraction solvent and volume, extraction conditions, wavelength, blank, calibration standard or extinction coefficient, calculation equation, and biological and technical replication.

Organoleptic Assessment

Sensory colour and texture were evaluated on day 7 by 10 untrained adult panellists using three-point category scales. The final submission should report informed consent and ethical approval or exemption, sample coding, randomised presentation, serving conditions, panel independence, and score dispersion.

Data Analysis

Sensory scores were summarised using medians. Physicochemical data were analysed by ANOVA followed by Duncan's multiple range test at $\alpha = 0.05$ when significant. The final submission should specify software/version, experimental unit, assumption tests, transformation, handling of repeated observations, and exact P values and effect sizes.

RESULTS AND DISCUSSION

Weight Loss

Postharvest weight loss is largely caused by water evaporation and the consumption of respiratory substrates. Residual field heat increases respiration and transpiration, thereby accelerating ripening, tissue softening, and moisture loss and ultimately shortening commodity shelf life (Deglas, 2023; Distriani *et al*., 2025).

Table 1 shows that weight loss rose in every treatment as storage progressed, confirming the continued loss of moisture and respiratory substrates. Values on day 1 ranged only from 0.41% to 0.51% and were not significantly different. Treatment effects became evident on days 5, 9, and 14. At the final observation, H3, H4, and H5 had significantly lower weight loss than H0, H1, and H2. The untreated fruit recorded the greatest loss, reaching 9.34%.

Table 1. Effect of *hydrocooling* duration on weight loss

No	Treatment	Weight Loss (%)			
		Day 1	Day 5	Day 9	Day 14
1	Untreated	0.51 a	4.83 b	7.68 b	9.34 b
2	5-minute *hydrocooling*	0.44 a	4.46 b	6.57 b	9.34 b
3	10-minute *hydrocooling*	0.45 a	4.32 ab	6.13 a	8.17 b
4	15-minute *hydrocooling*	0.46 a	3.36 a	5.13 a	7.03 a
5	20-minute *hydrocooling*	0.44 a	3.47 a	5.22 a	7.26 a
6	*Hydrocooling* 25 minutes	0.41 a	3.69 ab	5.44 a	7.72 a

Note: Numbers followed by the same letter in the same column indicate no significant difference based on the DMRT test at the 5% level.

The smaller losses under H3–H5 indicate that immersion for 15–25 min removed field heat sufficiently to reduce respiration and transpiration. Cold water transfers heat rapidly from the fruit tissue and lowers its initial temperature, thereby

moderating metabolism during subsequent storage (Ngadiono *et al*., 2019). Kabir *et al*. (2020) likewise found that prompt postharvest cooling delayed tomato deterioration, including weight loss. Gomes *et al*. (2023) further demonstrated that hydrocooling can preserve quality by limiting physiological activity and transpiration-related water loss.

Firmness level

Firmness was evaluated destructively with a penetrometer at the upper, central, and lower portions of the fruit. This variable represents the resistance of tomato tissue to an applied force and provides a direct indication of textural change during ripening and storage.

Firmness decreased during storage. Differences were present on day 1, with H0 at 1.80 kg cm^{-2} and cooled treatments at 2.27-2.55 kg cm^{-2}. H3–H5 generally retained greater firmness during storage. However, the H5 day-5 value and significance letter in Table 2 are internally inconsistent and must be verified against raw data before interpretation.

The stronger firmness retention under H3–H5 suggests that adequate hydrocooling lowered the internal fruit temperature and suppressed respiration, transpiration, and softening-enzyme activity. In untreated tomatoes, residual field heat likely accelerated pectin depolymerization and degradation of the cellulose–hemicellulose matrix, weakening cell-wall structure and producing more rapid softening (Fitriani *et al*., 2022; Zhu *et al*., 2022).

This interpretation is supported by Naibaho *et al*. (2025), who reported better firmness retention in hydrocooled tomatoes than in fruit stored without pre-cooling.

Table 2. Effect of *hydrocooling* duration on firmness

No	Treatment	Hardness Level (kg/cm²)			
		Day 1	Day 5	Day 9	Day 14
1	Untreated	1.80 a	1.72 a	1.55 a	1.50 a
2	5-minute *hydrocooling*	2.27 b	2.12 b	2.17 b	1.90 b
3	10-minute *hydrocooling*	2.47 bc	2.40 c	2.32 bc	2.25 c
4	15-minute *hydrocooling*	2.47 bc	2.60 d	2.55 d	2.52 d
5	20-minute *hydrocooling*	2.55 c	2.47 d	2.47 d	2.40 cd
6	*Hydrocooling* 25 minutes	2.52 c	1.72 d	2.47 d	2.35 cd

Note: Numbers followed by the same letter in the same column indicate no significant difference based on the DMRT test at the 5% level.

Total Soluble Solids

Total soluble solids (TSS), expressed in °Brix, represent sugars, organic acids, minerals, and other soluble constituents of tomato juice. TSS is widely used as an indicator of flavour development and maturity. During ripening, carbohydrate metabolism and the accumulation of simple sugars generally cause the value to increase (Xu *et al*., 2025).

TSS increased during storage in all treatments, although the magnitude of change differed. On day 1, values ranged from 2.62 to 3.37 °Brix and were statistically similar. Differences emerged on days 5, 9, and 14. At the final observation, H0 had the highest TSS at 4.00 °Brix and differed significantly from the hydrocooled treatments. H3, H4, and H5 retained lower values and showed a slower rate of increase (Table 3).

An increase in TSS is characteristic of climacteric-fruit ripening and reflects continued respiratory and metabolic activity.

As tomatoes ripen, reserve carbohydrates are broken down into simple sugars, while changes in organic-acid concentrations alter the overall balance of soluble compounds (Mudaffar & Haruna, 2024; Baihaqi & Fridayati, 2024). The lower TSS under H3–H5 indicates that effective field-heat removal moderated respiration and delayed these biochemical transformations. In contrast, the higher initial temperature of untreated fruit accelerated ripening and carbohydrate conversion. The degradation of cell-wall pectin and other carbohydrate fractions can also contribute to the accumulation of soluble sugars (Al-Dairi *et al*., 2021).

Table 3. Effect of hydrocooling duration on total soluble solids

No	Treatment	TSS (°Brix)			
		Day 1	Day 5	Day 9	Day 14
1	Untreated	3.37 a	3.50 b	3.62 b	4.00 c
2	5-minute *hydrocooling*	3.25 a	3.25 ab	3.62 b	3.37 b
3	10-minute *hydrocooling*	2.87 a	3.00 ab	3.37 ab	3.37 b
4	15-minute *hydrocooling*	2.75 a	2.75 a	3.00 a	3.00 a
5	20-minute *hydrocooling*	2.62 a	2.87 a	3.25 ab	3.25 a
6	*Hydrocooling* 25 minutes	2.75 a	3.00 a	3.00 a	3.12 a

Note: Numbers followed by the same letter in the same column indicate no significant difference based on the DMRT test at the 5% level.

Vitamin C

Vitamin C, or ascorbic acid, is nutritionally important but susceptible to oxidation during storage. Its stability depends on temperature, oxygen exposure, storage duration, and the physiological state of the fruit. Postharvest treatments that moderate metabolism may therefore improve vitamin C retention (Giannakourou & Taoukis, 2021) (Table 4).

Vitamin C increased between days 1 and 14 in every treatment. Initial values ranged from 5.52 to 6.80 mg/100 g and did not differ significantly. Treatment differences became evident on day 14, when H5 recorded the highest concentration at 13.77 mg/100 g.

The H5 value differed significantly from H0 and H1, while H2–H4 formed intermediate statistical groups. Overall, hydrocooling for 15–25 min was more effective than the control in maintaining vitamin C during storage.

The observed increase indicates that ripening-related vitamin C metabolism remained active during storage. Ascorbic acid may accumulate through ongoing biosynthesis and recycling pathways (Mellidou *et al*., 2021). These pathways are regulated by hormonal and transcriptional signals; endogenous hormones such as abscisic acid and methyl jasmonate can influence the expression of genes involved in vitamin C synthesis (Zheng *et al*., 2022). Hydrocooling probably enhanced vitamin C retention by lowering the initial tissue temperature and slowing both respiration and ascorbic acid oxidation. This explanation is consistent with Al-Dairi *et al*. (2021), who linked changes in nutrient composition to postharvest physiological conditions, and with Chepngeno *et al*. (2016), who reported that hydrocooling helped stabilize vitamin C during storage.

Table 4. Effect of *hydrocooling* duration on vitamin C

No	Treatment	Vitamin C (mg/100 g)	
		Day 1	Day 14
1	Untreated	5.59 a	7.25 a
2	5-minute *hydrocooling*	5.92 a	7.77 a
3	10-minute *hydrocooling*	5.67 a	10.07 ab
4	15-minute *hydrocooling*	5.52 a	11.78 ab
5	20-minute *hydrocooling*	6.42 a	12.30 ab
6	*Hydrocooling* 25 minutes	6.80 a	13.77 b

Note: Numbers followed by the same letter in the same column indicate no significant difference based on the DMRT test at the 5% level.

Carotenoids

Carotenoids are responsible for much of the red colour developed during tomato ripening (Kapoor *et al*., 2022). This colour transition involves chlorophyll degradation, conversion of chloroplasts into chromoplasts, and the regulated accumulation of lycopene and β-carotene (Zhu *et al*., 2022).

Carotenoid content increased from day 1 to day 14 in all treatments. Initial values of 0.0042–0.0048 mg/g did not differ significantly. By day 14, H0 had the highest concentration at 0.0151 mg/g and was significantly higher than H3, H4, and H5. Treatments H1 and H2 occupied an intermediate statistical position and did not differ significantly from either the control or the longer hydrocooling treatments (Table 5).

Lower carotenoid concentrations under H3–H5 indicate that longer hydrocooling delayed pigment development by removing more field heat and reducing the initial tissue temperature. Slower respiration and metabolism postponed ripening and lycopene synthesis relative to untreated fruit (Chepngeno *et al*., 2016). Ali *et al*. (2025) similarly reported that cold-water pre-cooling delayed visible colour change in horticultural produce. The present carotenoid pattern therefore reflects a slower physiological transition toward fully ripe red fruit (Al-Dairi *et al*., 2021).

Table 5. Effect of hydrocooling duration on carotenoid content

No	Treatment	Carotenoids (mg/g)	
		Day 1	Day 14
1	Untreated	0.0048 a	0.0151 b
2	5-minute *hydrocooling*	0.0044 a	0.0145 ab
3	10-minute *hydrocooling*	0.0043 a	0.0145 ab
4	15-minute *hydrocooling*	0.0043 a	0.0126 a
5	20-minute *hydrocooling*	0.0044 a	0.0126 a
6	*Hydrocooling* 25 minutes	0.0042 a	0.0125 a

Note: Numbers followed by the same letter in the same column indicate no significant difference based on the DMRT test at the 5% level.

Organoleptic

Organoleptic testing uses sensory responses to describe product condition and consumer acceptance. In this study, colour and texture scores varied according to hydrocooling duration (Table 6).

Color

Tomato colour provides a visible indication of ripeness and is primarily associated with lycopene accumulation (Baihaqi & Fridayati, 2025). H0, H1, and H2 received higher colour scores than H3, H4, and H5, showing that red-colour development occurred more rapidly when cooling was absent or brief. Longer hydrocooling lowered initial fruit temperature and slowed respiration, ripening metabolism, and pigment formation. This response agrees with the carotenoid results, in which H0 produced the highest concentration. Tomato colour development during storage is therefore closely connected with physiological activity and ripening-related pigment changes (Nazmi & Hariono, 2024; Muhanniah *et al*., 2021).

Texture

Texture is a practical indicator of tomato freshness because it reflects structural changes in the tissue during ripening. Softening results largely from pectin metabolism and the action of cell-wall-degrading enzymes (Al-Dairi *et al*., 2021). Treatments H3, H4, and H5 received higher texture scores than H0, H1, and H2, indicating that the longer cooling durations retained firmer fruit. Adequate hydrocooling can reduce respiration and transpiration, limit moisture loss, and preserve cell turgor (Ridwan *et al*., 2022). Untreated tomatoes, in contrast, lose water more rapidly and consequently develop softer tissue and surface wrinkling. These sensory observations correspond with the instrumental firmness results.

Table 6. Median values of organoleptic test results for tomatoes (*Solanum lycopersicum L*.) during storage

No	Treatment	Color	Texture
1	Untreated	2	2
2	5-minute *hydrocooling*	2	2
3	10-minute *hydrocooling*	2	2
4	15-minute *hydrocooling*	1	3
5	20-minute *hydrocooling*	1	3
6	25-minute *hydrocooling*	1	3

Notes: Color attributes were rated on a 1–3 scale (1 = yellowish red; 2 = bright red; 3 = uniform red), while texture was rated on a 1–3 scale (1 = very soft; 2 = soft; 3 = somewhat hard).

CONCLUSION

Hydrocooling for 15–25 min reduced quality deterioration in Mustafi tomatoes during 14 days of ambient storage. These treatments resulted in lower weight loss, greater firmness, lower total soluble solids, higher vitamin C, slower carotenoid accumulation, delayed colour development, and firmer sensory texture than untreated fruit. Fifteen minutes produced outcomes comparable to longer immersion durations while requiring less treatment time. This conclusion is limited to the tested cultivar and conditions; commercial recommendation requires verification of pulp cooling, water sanitation, decay incidence, safety, water use, and economic feasibility.

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