

Orchard applications of sodium hydrosulfide increase the yield of avocado (*Persea americana* Mill.) cv. 'Hass'

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Abstract

Background

Avocado (*Persea americana* Mill.) ‘Hass’, the globally dominant cultivar, is susceptible to winter frost and spring-summer heatwaves. The latter can intensify immature fruit abscission (‘June drop’). Hydrogen sulfide (H_2S) is an endogenous signaling molecule known to prime plants against multiple abiotic stresses and inhibit organ abscission. Our prior studies demonstrated the beneficial effects of priming ‘Hass’ trees with the H_2S donor sodium hydrosulfide (NaHS) against cold stress. Based on these, the current study evaluated the impact of combined winter and summer NaHS applications on commercial ‘Hass’ fruit yield.

Results

A 3-year field trial was conducted using 80 ‘Hass’ trees [40 control (CR) and 40 NaHS-treated trees], with spray treatments applied three times in winter and three times in early summer each year. Notably, NaHS-treated trees exhibited consistently higher yields than CR trees across all three study years, resulting in a cumulative yield increase of $\sim 35\%$ by weight and $\sim 48\%$ by fruit number. Spatial assessment of individual tree yields and the alternate bearing index revealed that the orchard plot was asynchronous, demonstrating that the NaHS-induced yield increase was independent of the trees’ baseline physiological bearing state.

Conclusions

The established anti-abscission properties of H_2S combined with the temporal overlap of summer NaHS applications with the natural fruit drop period, strongly suggest that exogenous H_2S mitigates premature avocado fruitlet abscission. Pending the development of suitable agricultural formulations, orchard NaHS application presents a powerful, promising agronomic strategy to enhance climate resilience, prevent pre-harvest crop loss and stabilize commercial avocado yields.

Introduction

Fruit tree species of tropical and subtropical origin, such as avocado (*Persea americana* Mill.), are highly sensitive to temperature extremes (Schaffer et al., 2024). In particular, the widely cultivated ‘Hass’ variety may suffer severe yield losses when exposed to environmental stressors like frost and heatwaves (Ramírez-Gil et al., 2024). Beyond abiotic stress, orchard productivity and supply chain consistency can be constrained by alternate bearing – the physiological cycles between high and low yield years (Goldschmidt & Sadka, 2021; Monselise & Goldschmidt, 1982). Young avocado ‘Hass’ trees are especially sensitive to environmental and physiological fluctuations (Lahack et al., 2025), which can

delay tree establishment and limit yield. Crucially, stabilizing mature fruit tree orchards against severe weather disturbances remains a major challenge for global fruit production.

Chemical priming has emerged as a promising strategy to mitigate the effects of environmental extremes on plants (Chaudhary et al., 2025; Gohari et al., 2024). Priming involves the pre-treatment of plants with specific compounds that induce a pre-conditioned state, allowing for faster and more robust responses to stress. One common priming compound is hydrogen sulfide (H_2S), an endogenous signaling molecule that plays a critical role in various plant processes including growth, development, and stress adaptation (Corpas & Palma, 2020; Jaiswal et al., 2025; Silveira et al., 2024). H_2S , commonly provided using the donors sodium hydrosulfide (NaHS) or sodium sulfide (Na_2S), has been shown to alleviate multiple abiotic stresses, including cold, heat, salinity, drought and heavy metal stress (Raza et al., 2022; Zulfiqar & Hancock, 2020). Such stress conditions result in the generation of excess reactive oxygen species (ROS) and damage to cellular components. H_2S mitigates these adverse effects by stimulating antioxidant defense systems, which scavenge or detoxify ROS, thereby promoting redox homeostasis (Jaiswal et al., 2025; Khanna et al., 2021).

Our earlier studies focused on priming with NaHS to improve the response of avocado 'Hass' trees to frost. We found that young trees pre-treated with NaHS responded better to a (simulated) frost night (Joshi et al., 2020). The beneficial effects in primed trees included higher photosynthetic CO_2 assimilation rates and a reduced accumulation of ROS (H_2O_2), compared to non-primed trees, after the frost exposure. Transcriptome analysis in this young tree model revealed that NaHS priming induced the expression of genes associated with cellular protection and stress responses (Tiwari et al., 2024). Scaling up these findings to field trials, NaHS treatments were applied to mature 'Hass' trees in the orchard both as targeted pre-treatments to a frost alert and as 'routine' winter treatments. Although frost did not occur, we observed that following natural chilling, NaHS-treated trees exhibited improved gas exchange parameters compared to non-primed trees (Tiwari et al., 2023, 2024).

Aside from its sensitivity to cold, 'Hass' is also sensitive to heat spells (Lazare et al., 2022), which can cause intense fruit abscission in spring and early summer. This phenomenon is referred to as 'June drop' in the Northern Hemisphere (Garner & Lovatt, 2008, 2016), and can result in massive seasonal yield and economic losses. As described above, H_2S improves plant responses to multiple abiotic stresses including heat stress. Notably, H_2S has also been shown to reduce organ abscission (Hilal et al., 2023; Liu et al., 2020, 2022). These considerations, along with our earlier results demonstrating the beneficial NaHS priming of 'Hass' under cold stress (Joshi et al., 2020; Tiwari et al., 2023, 2024), motivated us to test whether NaHS treatment of 'Hass' in summer can reduce fruit drop. Thus, the aim of the current work was to conduct a rigorous orchard evaluation to determine whether combined winter and summer spray applications of NaHS can mitigate environmental crop loss and optimize the multi-year commercial fruit yield of 'Hass' avocado.

Materials and Methods

Orchard site and experimental setup

The study was carried out in a commercial avocado orchard in Giv'at Brenner (31°51'44.4"N, 34°47'04.3"E) between 01/2023 to 01/2026, on 'Hass' trees grafted on seedling 'West Indian' rootstocks. The plot was planted in 2017, with 7-m spacing between rows and 4-m spacing between trees within each row. The study included 80 trees: 40 control ('CR') trees and 40 sodium hydrosulfide-treated ('NaHS') trees. Similar trees were selected and arranged in 4-tree 'blocks', with spacing included to omit poor or unhealthy trees, or spaces of trees that did not survive prior to the study (Figure S1). To prevent row variations, CR and NaHS trees were mixed within the same rows.

Daily minimal and maximal air temperatures were extracted from temperature data of a nearby meteorological station collected at a 2-m height and 10-min intervals ('Beit Gamliel'; <https://www.meteo.co.il/>).

Sodium hydrosulfide (NaHS) spray treatments

Trees were sprayed with a freshly prepared solution of 200 µM NaHS (Sigma-Aldrich), 0.05% (v/v) TWEEN 20 (Sigma-Aldrich), between 15:00–16:00 in the winter and between 17:00–18:00 in the summer. Each tree was sprayed with ~ 4 L of the solution.

Flowering and foliage cover assessment and fruit harvest

Flowering and foliage cover were visually assessed in the spring of each year. Flowering intensity was scored between 0 (low) and 5 (high), and foliage (leaf) cover was scored between 0 (no foliage) to 3 (high foliage cover). Representative tree scoring examples are shown in Figure S2. Harvest dates followed farmer considerations and market demand. Fruit was harvested from each experimental tree separately, and fruit counted and weighed (in bulk) for the tree.

Alternate bearing index (*ABI*) was calculated as (Hoblyn et al., 1936):

$$ABI = \frac{| \text{yield year}_x - \text{yield year}_{x-1} |}{\text{yield year}_x + \text{yield year}_{x-1}}$$

Statistical analysis

The statistical analyses were performed in R v4.4.1 using the lme4 v1.1-37 and emmeans v1.11.1 packages (Bates et al., 2015; Lenth, 2025; R Core Team, 2024). To assess the yield for individual years, one-way ANOVA was conducted with treatment included as a fixed factor. Cumulative yield data were analysed using a linear mixed-effects model fitted with the lmer function from the lme4 package. The

model included Treatment, Year, and their interaction (Treatment $\times$ Year) as fixed effects, while tree number was included as a random effect to account for repeated observations from the same tree across years. Estimated marginal means were calculated using the emmeans package, and Dunnett's test was performed to compare the treatment against the control group.

Results

The orchard site selected for the study is located at a specific plot identified to be particularly prone to cold damage. Forty 'Hass' trees were selected for sodium hydrosulfide treatment ('NaHS') and forty served as control ('CR'). Trees of similar size were selected, with NaHS and CR trees arranged ten 'blocks' of four trees (Figure S1). Spacing within or between blocks, especially in rows 12–15, is due to trees that did not survive prior to the study or ones omitted due to their poor size or health.

NaHS trees were sprayed three times in winter and three times in summer (Table 1), with winter sprays targeted to the cold period of winter, and summer sprays to the period characterized by fruit drop during June (June drop). In the first year (2023) only two spray treatments were applied in winter due to a prolonged rainy season and limited access to the orchard (Table 1). Assessment of flowering and foliage in the spring of this year showed that all trees flowered at maximal intensity, accompanied by very low foliage cover (mean scores < 1) in both tree groups (Table 2). Fluctuation of the maximal daily temperature can be seen from March to around mid-June; several days exhibited maximal temperatures $> 35^{\circ}\text{C}$ and one day had a maximal temperature $> 40^{\circ}\text{C}$ (Fig. 1a). June spray applications were provided ~ 2 weeks apart (Table 1). Fruit harvest in the first year (January 2024) showed that NaHS-treated trees had $\sim 40\%$ more yield than CR trees, both by weight [mean 29.72 (NaHS) vs 21.26 (CR) kg tree^{-1} ; Fig. 2a] and by number of fruit [mean 143 (NaHS) vs 102 (CR) fruit tree^{-1} ; Fig. 2b]. Due to the high variability between individual trees, the differences were not statistically significant. Average fruit weight was slightly reduced in NaHS trees, 227 g vs 250 g in CR trees (Fig. 2c).

Table 1
Timeline of NaHS applications and fruit harvest.

Year	Winter sprays	Summer sprays	Harvest [†]
2023–2024	Jan. 5, 2023 ¹	June 2, 2023	Jan. 2 & 8, 2024
	Feb. 9, 2023	June 15, 2023	
		June 29, 2023	
2024–2025	Feb. 13, 2024	June 2, 2024	Nov. 7 & 10, 2024 ²
	Feb. 26, 2024	June 17, 2024	Dec. 17 & 18, 2024
	Mar. 11, 2024	July 1, 2024	
2025–2026	Jan. 2, 2025	June 4, 2025	Dec. 9, 2025 &
	Jan. 13, 2025	June 26, 2025 ³	Jan. 8, 2026 ⁴
	Jan. 28, 2025	July 7, 2025	

[†] Harvest preceded the winter treatments of the respective production cycle.

¹ Only two winter applications were performed due to a heavy seasonal rainfall and restricted orchard access.

² Selective partial harvest conducted to supply early commercial market demand.

³ Application date delayed due to unforeseen circumstances.

⁴ Total crop harvest was completed in two sequential sessions.

Table 2
Visual scores [†] of flowering intensity and foliage cover.

Year	Treatment ¹	Flowering intensity ²	Foliage cover ³
2023	CR	5.00 ⁴	0.58 ± 0.42
	NaHS	5.00 ⁴	0.83 ± 0.48
2024	CR	4.23 ± 0.20	1.40 ± 0.15
	NaHS	3.95 ± 0.21	1.60 ± 0.15
2025	CR	3.41 ± 0.24	2.29 ± 0.10
	NaHS	2.55 ± 0.26*	2.53 ± 0.10

[†] Visual reference examples for canopy scoring are provided in Figure S2.

¹ The control (CR) and NaHS groups include 40 trees each; values shown are means $\pm$ SE.

² Flowering intensity was scored on a visual scale from 0 (no flowering) to 5 (maximal flowering).

³ Foliage cover scored on a visual scale between 0 (bare/no leaves) to 3 (dense foliage cover).

⁴ In the first year, all selected trees exhibited maximal flowering intensity.

* Indicates a statistically significant difference between treatments ($p < 0.05$).

Winter in the second year (2023–2024) was relatively warm in its first part (Fig. 1a, b). Spray treatments were therefore applied later in the season, beginning around mid-February (Table 1). Spring evaluation of the trees showed relatively high flowering intensity, with medium foliage cover, and no differences between the tree groups (Table 2). June spray applications were as in the first year (Table 1). In this year, selective fruit harvest (selectively picking large fruit from each tree) was carried out in November (2024) to supply market demand. During this harvest, somewhat more yield was collected from NaHS trees, $\sim 15\%$ more by weight and $\sim 21\%$ more by number than CR trees, with similar fruit size in both tree groups ('Yield-I'; Fig. 3a-c). Fruit harvest of the trees was completed about a month later, in December. Notably, the yield of NaHS trees was substantially higher than CR trees, with $\sim 93\%$ more yield by weight and $\sim 105\%$ more fruit by number ('Yield-II'; Fig. 3d, e). Expectedly, fruit from NaHS trees were smaller, with an average fruit weight of 173 g vs 223 g in CR trees (Fig. 3f). To consider the total yield of the trees, the yield of the two harvests was summed for each tree ('Yield-total'). This showed an overall significant increase of $\sim 46\%$ yield by weight [mean 61.62 (NaHS) vs 42.16 (CR) kg tree⁻¹; Fig. 3g] and $\sim 59\%$ increase by fruit number [mean 362 (NaHS) vs 228 (CR) fruit tree⁻¹; Fig. 3h] in NaHS trees compared to CR ones.

The three winter NaHS treatments of the third year were applied in January 2025, as this month began with chilling minimal temperatures, below 5°C (Table 1 and Fig. 1c). Nonetheless, lower minimal temperature occurred later in February, with one light frost morning on February 25 (Fig. 1c). Assessment of flowering showed that on average NaHS trees flowered less intensely than CR trees, while foliage cover was relatively high in both tree groups (2025; Table 2). Fluctuation of maximal daily temperature was observed during April-May with a couple of days crossing the 40°C mark (Fig. 1c). In the summer treatments, the second and third sprays were slightly delayed (Table 1). Harvest of this year showed that NaHS trees had more yield than CR trees also, with an increase of $\sim 20\%$ by weight [mean 39.99 (NaHS) vs 33.36 (CR) kg tree⁻¹; Fig. 4a] and $\sim 38\%$ by fruit number [mean 209 (NaHS) vs 152 (CR) fruit tree⁻¹; Fig. 4b], although not statistically significant. Average fruit weight was only slightly affected, with a mean of 242 g in CR vs 220 g in NaHS trees (Fig. 4c).

To assess the temporal and spatial impacts of NaHS treatment on 'Hass' tree productivity, individual tree yields (kg tree⁻¹) were mapped over the three-year period (Fig. 5). The visual heatmap highlights the high degree of variability inherent to avocado 'Hass'. For some individual trees, alternate bearing toggling

between “on” (high yield) and “off” (low yield) years is clearly evident (e.g. Trees 1, 7, 72, 73). However, on the orchard-level the alternate bearing pattern is not synchronized. For example, in Tree #5–8 block (NaHS), while Trees 5 and 6 follow an “off-on-off” pattern for years 1-2-3, Tree 7 exhibits an “on-off-on” one. Similarly in Tree #65–68 block (CR), Trees 65 and 66 are “off-on-off”, while Tree 68 is “on-off-on”. This demonstrates that even trees adjacent to each other behave differently. In addition, some trees were characterized by relatively low yield (e.g. Trees 13, 36, 44, 45), while others did not exhibit a clear-cut alternate bearing pattern during the studied period (e.g. Trees 3, 47, 51, 62). A corresponding yield heatmap for fruit number in individual trees over the three-year study is shown in Figure S3.

For assessment of multi-year tree productivity, we omitted trees that had a 3-year cumulative yield < 10 kg: CR trees #36 and 44 and NaHS trees #45 and 46 (Fig. 5). Analysis of the alternate bearing index (*ABI*) for the two pairs of consecutive years demonstrates a high variability among individual trees in both (CR, NaHS) groups (Fig. 6a). This variability supports the visually observed asynchrony in alternate bearing cycles across the orchard (Fig. 5). In year 1 vs 2 (2024–2025), trees exhibited a mean *ABI* of 0.59 (CR) and 0.55 (NaHS), and in year 2 vs 3 (2025–2026) a somewhat lower mean *ABI* of 0.45 (CR) and 0.38 (NaHS); no significant differences were found between the groups. Finally, to assess the multi-year effect of NaHS on yield, we examined the total 3-year yield of individual trees. The cumulative 3-year yield of NaHS trees was significantly higher, by ~ 35% in weight and ~ 48% in fruit number, compared to CR trees (Fig. 6b, c).

Discussion

Avocado trees flower extensively, yet their final reproductive success (yield) is particularly low due to substantial abscission of both flowers and fruit (Salazar-García et al., 2013). Thus, while a mature avocado tree can produce hundreds of thousands of flowers, its final fruit set is extremely low (< 0.1%) (Alcaraz & Hormaza, 2021; Hormaza et al., 2024). Harsh climate extremes along with alternate bearing cycles can further contribute to unstable or limited avocado fruit yields.

In the present study, we found that combined winter and summer foliar applications of NaHS increased the yield of avocado ‘Hass’ trees across three consecutive years. Tracking of eighty trees, analysis of their alternate bearing index (*ABI*), alongside the spatial assessment of tree yields (Figs. 5 and 6a), demonstrated that the orchard plot is asynchronous, even among immediately adjacent trees that are exposed to the same environmental conditions. Therefore, the yield increase attributed to the NaHS treatment over the three-year period is likely independent of the trees’ baseline physiological states. These results are further strengthened by the intentional selection of a cold-sensitive orchard plot and the use of trees grafted on seedling rootstocks (Cohen et al., 2023), both of which amplify natural tree variability.

‘Hass’ is characterized by immature fruit drop – ‘June drop’ (Garner & Lovatt, 2008, 2016), which can be intensified by heat events. The substantial increase in fruit number in NaHS-treated trees, particularly in year 2 of this study (+ 59% vs CR), combined with the temporal overlap of the summer treatments with

the June drop period, strongly suggests that NaHS mitigates fruit abscission. This proposal is further supported by the fact that reactive oxygen species (ROS) bursts within reproductive tissues activate the abscission cascade (Ma et al., 2021), while H₂S is well-known to modulate antioxidant systems for maintaining redox homeostasis (Jaiswal et al., 2025; Silveira et al., 2024). The phytohormones ethylene and auxin play major, antagonistic roles in this abscission process, with ethylene promoting organ separation and auxin delaying it (Meir et al., 2019; Taylor & Whitelaw, 2001). The critical role of ethylene in avocado yield limitation was recently highlighted by applications of the ethylene action inhibitor 1-MCP (1-Methylcyclopropene) on avocado cultivars 'Hass' and 'Gem' (Tabatznik et al., 2026). 1-MCP treatments during the flowering period led to significant increases in fruit set, and in some years also to an increase in yield in both cultivars. Treatments during early fruit set (mid-May to beginning of June) resulted in higher fruitlet survival rates in both 'Gem' and 'Hass', and to an increase in yield only in 'Hass' during one (determined) season (Tabatznik et al., 2026).

Notably, hydrogen sulfide (H₂S) is well-documented for its inhibitory effects on the ethylene pathway. Exogenous H₂S (provided as NaHS) has been shown to inhibit ethylene-induced abscission of petioles in tomato and of floral organs in rose (Liu et al., 2020). Furthermore, H₂S also inhibits the initiation of tomato pedicel abscission, and transcriptome analysis of these tissues revealed that H₂S modulates both the auxin and ethylene signaling pathways (Liu et al., 2022). The most characterized molecular mode of action of H₂S is protein persulfidation – a post-translational modification converting a cysteine thiol (-SH) into a persulfide group (-SSH) (Vignane & Filipovic, 2023; Wang et al., 2021). Persulfidation can alter protein function by modifying activity, structure, stability or cellular localization (Aroca et al., 2018). The inhibitory effect of H₂S on the ethylene pathway has been connected to persulfidation of specific proteins. ACO enzymes (1-aminocyclopropane-1-carboxylic acid oxidases) catalyze the second reaction of ethylene biosynthesis, which is rate-limiting during certain processes (Houben & Van de Poel, 2019). In tomato, persulfidation of ACOs was shown to inhibit their enzymatic activity, thereby negatively regulating ethylene biosynthesis under osmotic stress (Jia et al., 2018). Additional findings in tomato show that persulfidation of the ethylene response factor SIERF.D2 also delays ethylene biosynthesis and fruit ripening (Sun et al., 2025).

Although the current study did not delve into molecular and biochemical outcomes of H₂S signaling in the orchard, the multi-year agronomic outcomes strongly support the established pathways described above. NaHS treatments of 'Hass' trees in June likely triggered H₂S-mediated inhibition of the ethylene pathway, resulting in a reduction of fruit drop. Following the relatively high yield of NaHS trees in year 2, average flowering intensity in these trees in year 3 was lower than that of CR trees (Table 2). A negative correlation between tree yield and flowering in the subsequent year is a well-established phenomenon in avocado, forming the physiological basis for alternate bearing, due to carbohydrate depletion and hormone-mediated flowering repression (Pochamreddy et al., 2024; Salazar-García et al., 1998; Scholefield et al., 1985; Smith & Samach, 2013; Whiley et al., 1996). This negative relationship is clearly visible at the individual tree level for both CR and NaHS groups (Figure S4). Strikingly, although NaHS trees flowered less intensely on average in year 3, they still yielded more fruit than CR trees. This

observation not only reinforces the proposed anti-abscission effect of NaHS, but also suggests that H₂S can modify the tree sink-source tradeoff, enabling higher fruit retention even when reproductive effort (flowering) is reduced.

Examination of the relationship between tree flowering, leaf cover and yield in year 3 revealed a distinct pattern for CR vs NaHS trees (Figure S5). In both tree groups, heavy flowering was generally accompanied by reduced foliage cover, reflecting the known competition for carbohydrate reserves between the spring vegetative flush and reproductive organs (Whiley et al., 1988; Wolstenholme & Whiley, 1989). Untreated CR trees that flowered profusely (scored 4–5) but lacked sufficient foliage cover (scored ≤ 1.5) often resulted in relatively poor final yields (Figure S5a), likely due to carbohydrate exhaustion and subsequent flower/fruitlet abscission. High yields in CR trees were observed in trees that had relatively high flowering (scored > 3) combined with high foliage cover (scored 2–3). This demonstrates that high flowering does not guarantee high yield but rather highlights the crucial need for an adequate photosynthetic canopy (source). On the other hand, in NaHS-treated trees, high yields were achieved even in trees that exhibited only low-to-moderate flowering intensity (scored 1–3) alongside robust foliage cover (scored 2–3) (Figure S5b). Thus, NaHS enabled the trees to better support and retain a higher crop load (sink) without the severe metabolic exhaustion typically associated with intense flowering. This canopy-yield relationship strongly aligns with the recent work by Shahar et al. (Shahar et al., 2026), who demonstrated that foliar application of gibberellic acid (GA₃), which increased foliage cover and protected young ‘Hass’ trees from heat stress, resulted in increased fruitlet retention and higher yields even though flowering levels were reduced.

While the temporal overlap of the summer NaHS treatments with the June drop period strongly points to the mitigation of fruitlet abscission, the specific contribution of the winter treatments remains to be determined. Our earlier results demonstrated beneficial effects of NaHS under cold conditions (Tiwari et al., 2023, 2024). We therefore originally targeted the winter treatments to improve the response to low temperatures in a plot highly prone to cold damage. It is plausible that the winter sprays provided improved cold tolerance, protecting early floral bud development and maintaining photosynthetic integrity during the colder months, which subsequently supported the summer crop load. Future studies testing separate winter-only and summer-only treatments are required to determine the relative effect of each application window in positively affecting fruit yield.

Finally, from a practical agronomic perspective, the transition of H₂S from a recognized endogenous signaling molecule to a field-applied product holds significant promise for stabilizing high-value perennial food crops. NaHS is a highly soluble, cost-effective H₂S donor, making foliar applications economically viable for commercial avocado orchards. However, the rapid release and high volatility of H₂S from NaHS solutions present challenges for precise, long-acting dosing under open-field conditions. Future development and optimization of slow-release H₂S donors, e.g. (Carter et al., 2018, 2019), tailored for agricultural use may provide a powerful tool for modulating source-sink balance, minimizing pre-harvest losses, and thereby enhancing the yield of avocado and possibly other fruit trees.

Declarations

Author contributions

Conceptualization: I.K., D.C.; Methodology: I.K., P.R., M.B., D.C.; Investigation: I.K., P.R., M.B., C.D., M.C., S.G.; Formal analysis: I.K., P.R., D.C.; Visualization: P.R., D.C.; Supervision, Funding acquisition, and Writing – original draft: D.C.; Writing – review & editing: I.K., P.R., M.B., C.D., M.C., S.G.

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Conflict of interest statement

The authors declare they have no known conflict of interests.

Data availability statement

Yield data is available in Supplementary Table S1. Other data will be made available upon reasonable request from the corresponding author.

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Figures

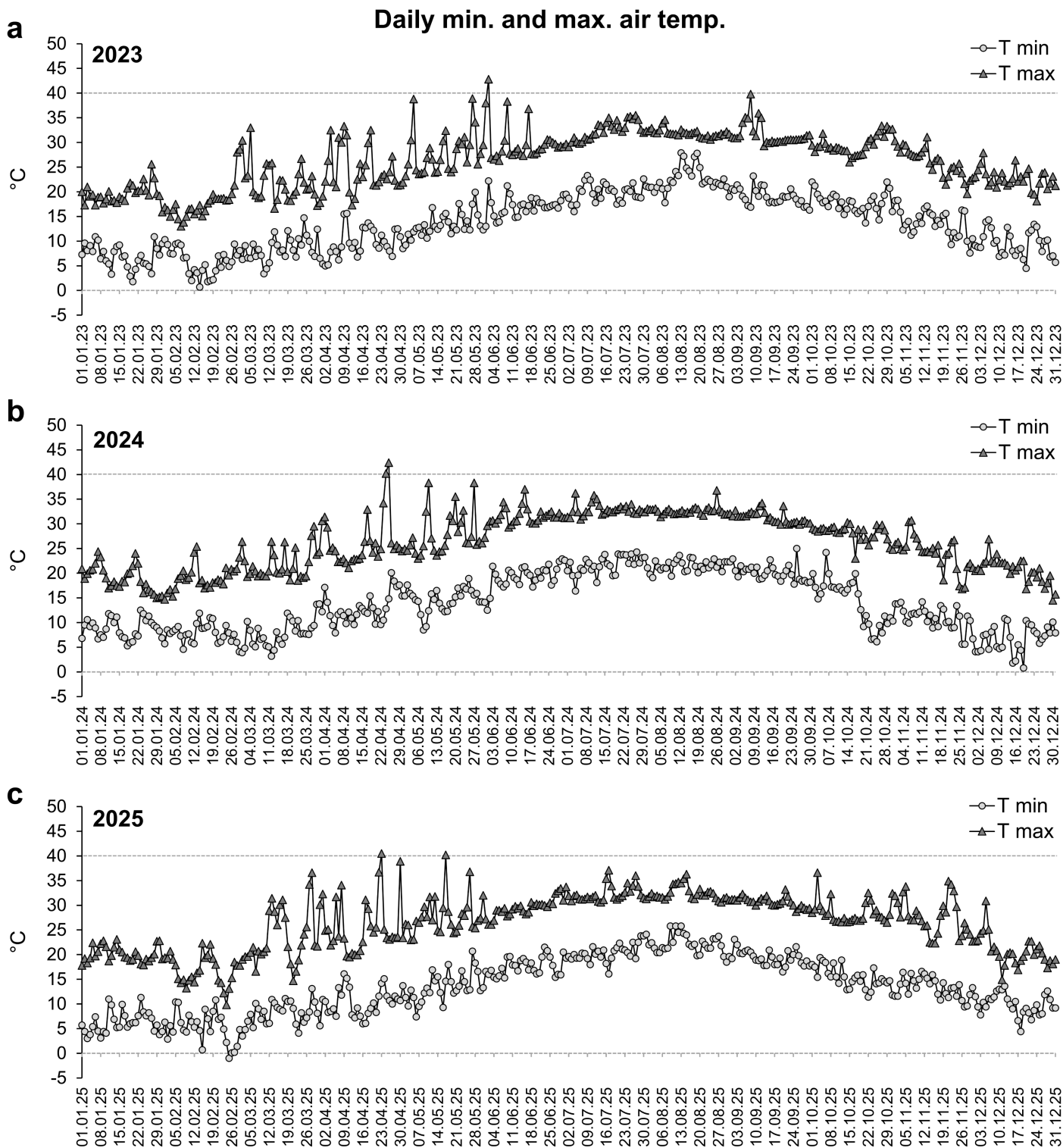


Figure 1

Daily minimum and maximum air temperatures. Data presented for **(a)** 2023, **(b)** 2024, and **(c)** 2025 illustrate seasonal temperature dynamics. Dashed gray lines mark temperature extremes of 0°C and 40°C.

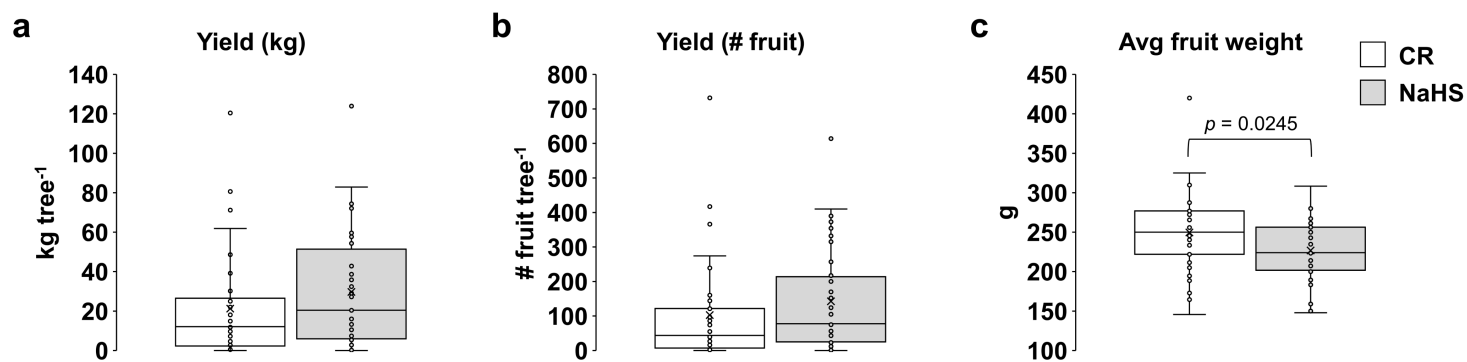


Figure 2

Fruit yield in the first year (2023–2024). Yield of individual trees from control (CR) and NaHS-treated groups is shown in **(a)** kg tree⁻¹ and **(b)** number of fruit tree⁻¹, and **(c)** calculated average fruit weight. For both groups, $n = 40$ trees; the significant difference between CR and NaHS in (c) is noted by the p -value. Data and detailed statistical analyses are provided in Table S1.

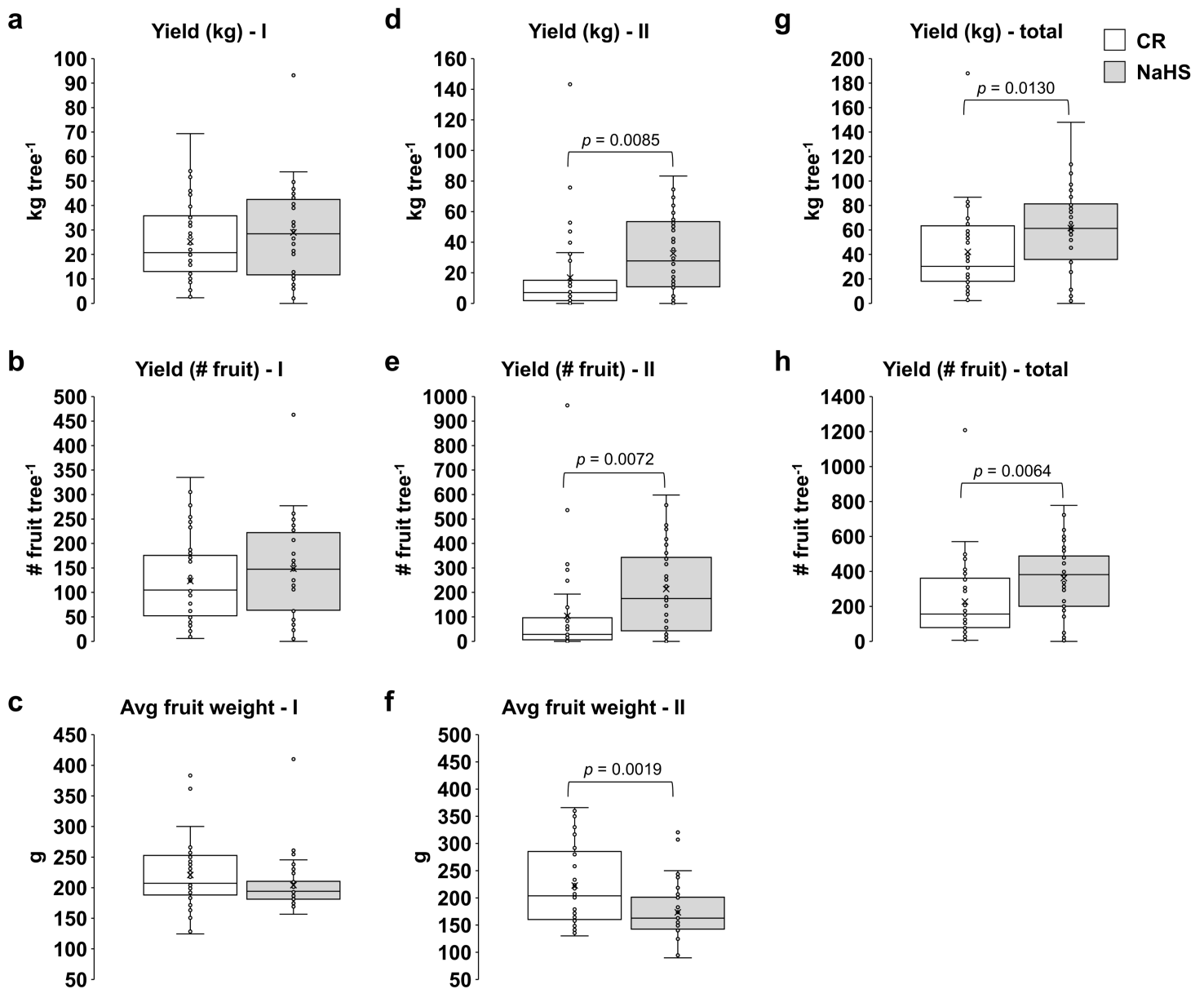


Figure 3

Fruit yield in the second year (2024–2025). The yield was harvested in two stages: **(a–c)** Harvest 'I' – selective harvest of large fruit, and **(d–f)** Harvest 'II' – complete harvest of all remaining fruit. **(g, h)** 'Total' yield – sum of Harvests 'I' and 'II' for each individual tree. The yield of individual trees from control (CR) and NaHS-treated groups is shown in **(a, d, g)** kg tree⁻¹ and **(b, e, f)** number of fruit tree⁻¹, along with **(c, f)** calculated average fruit weight for Harvests 'I' and 'II'. For both groups, n = 40 trees; statistically significant differences between CR and NaHS are noted by their *p*-values. Data and detailed statistical analyses are provided in Table S1.

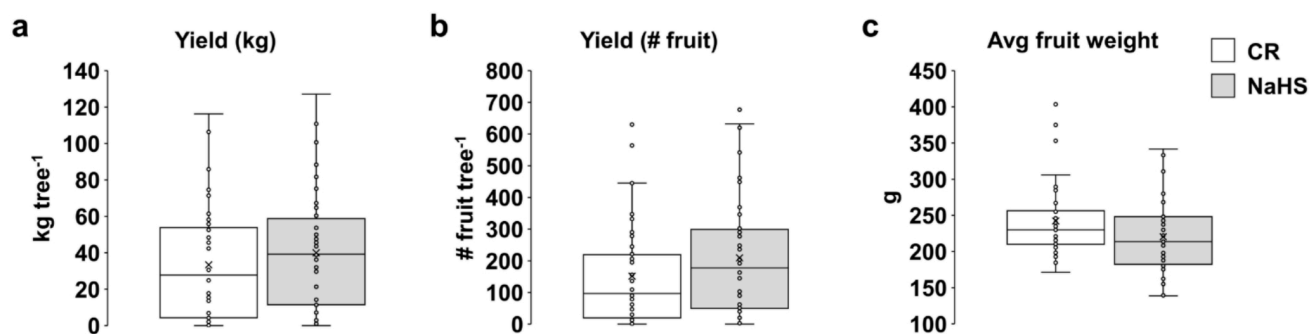


Figure 4

Fruit yield in the third year (2025–2026). The yield of individual trees from control (CR) and NaHS-treated groups is shown in **(a)** kg tree⁻¹ and **(b)** number of fruit tree⁻¹, and **(c)** calculated average fruit weight. For both groups, $n = 40$ trees; no statistically significant differences between CR and NaHS were detected. Data and detailed statistical analyses are provided in Table S1.

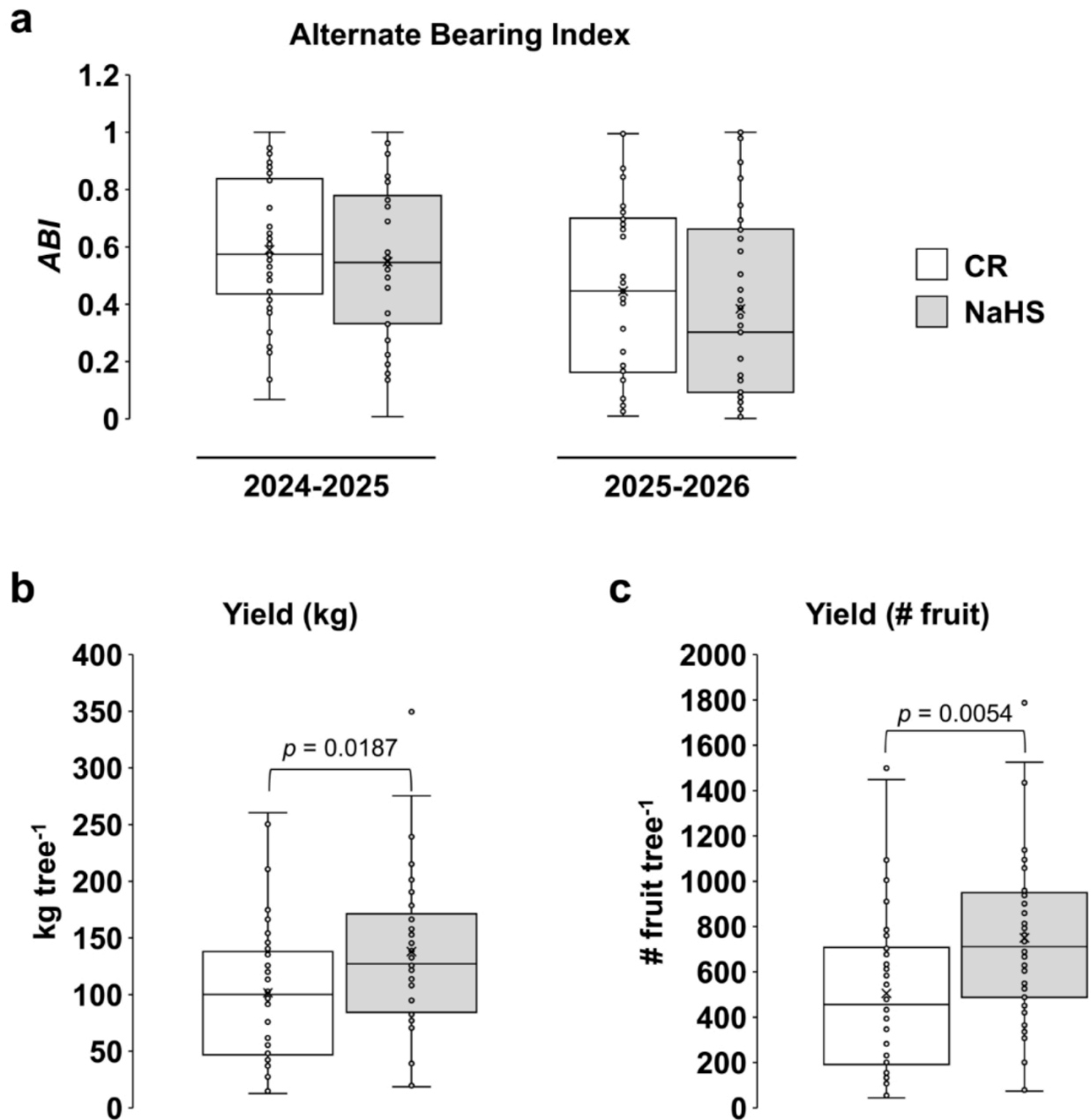


Figure 6

Alternate bearing index and the cumulative three-year yield of control (CR) and NaHS-treated avocado trees. (a) The alternate bearing index (ABI) was calculated for consecutive seasons (2024–2025) and (2025–2026). The cumulative three-year yield of individual trees from control (CR) and NaHS-treatment groups is shown in (b) kg tree⁻¹ and (c) number of fruit tree⁻¹. Trees with a three-year cumulative yield < 10 kg (two CR and two NaHS trees) were omitted from the analysis. For both groups, n = 38 trees;

statistically significant differences between CR and NaHS are indicated by their exact p -values. Data and detailed statistical analyses are provided in Table S1.

Supplementary Files

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