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Article

Effects of Hot Water Treatment on Plant Performance, Bud Break, and Yield in Strawberry and Raspberry

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Abstract

Hot water treatment (HWT) is a promising non-chemical method for controlling pests and pathogens in horticultural crops, aligning with the increasing demand for sustainable and residue-free production systems. This study evaluated the effects of various HWT protocols on plant vigour, yield, and fruit weight in strawberry (*Fragaria* × *ananassa*) and raspberry (*Rubus idaeus*) under protected cultivation in Switzerland. Strawberry tray plants were treated at 18–20 °C (ambient), 37 °C, or 47 °C for 10 min prior to planting. Raspberry canes were treated at 18–20 °C, 40 °C, or 45 °C for either 10 or 60 min. In strawberries, no significant differences were observed in the number of flowering stems, flowers, yield per plant, and fruit weight. However, a trend towards lower yields and higher fruit weights has been observed at higher treatment temperatures, particularly 47 °C. In raspberries, bud break was negatively affected by higher temperatures, while leaf area, cumulative yield, and fruit weight remained unchanged across treatments. These results suggest that HWT can be integrated into berry production with minimal impact on plant performance, provided treatment parameters are carefully optimized. Further research is needed to evaluate pest control efficacy under real infestation conditions and to refine protocols for different cultivars and developmental stages.

Keywords: hot water treatment; berry crops; *Fragaria* × *ananassa*; *Rubus idaeus*; bud break; yield; plant performance; thermal stress

1. Introduction

The cultivation of berry crops such as strawberry and raspberry faces increasing challenges due to evolving pest pressures and stringent market quality standards. The growing demand for high-quality produce necessitates a reduction in synthetic pesticide use, in line with consumer expectations and regulatory requirements. This shift is further complicated by the emergence of new pests and diseases, partly driven by climate change and global trade [1,2]. In organic production systems, where synthetic pesticides are prohibited, the need for effective alternative pest management strategies is particularly acute. Moreover, continuous harvesting cycles of berry crops limit the use of conventional pesticides, as pre-harvest intervals often exceed the time between harvests, rendering chemical control impractical or impossible [3]. Consequently, there is a strong need to develop innovative and sustainable approaches that ensure both crop protection and stable production. In this context, increasing regulatory restrictions, rising costs of plant protection products, and growing concerns over pesticide residues further highlight the importance of alternative, residue-free control strategies in modern berry production systems.

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Plants are continuously exposed to a wide range of environmental constraints that can be broadly classified into biotic and abiotic stresses. While biotic stresses arise from interactions with pests and pathogens, abiotic stresses include temperature extremes, drought, salinity, and radiation. Among these, temperature-related stress is a key factor influencing plant growth and productivity in horticultural systems. Elevated temperatures can disrupt cellular homeostasis, impair enzymatic activity, and affect reproductive processes such as flowering and fruit set, ultimately leading to yield losses and reduced crop performance [4,5]. In perennial fruit crops, including berry species, these effects are particularly critical during sensitive developmental stages, where even short-term exposure to stress can have lasting impacts on plant performance and productivity. Furthermore, the increasing diversification of cultivars and production systems (e.g., protected cultivation, soilless systems) requires a better understanding of how plants respond to controlled thermal conditions across different agronomic contexts.

At the physiological level, plant responses to temperature stress involve changes in membrane stability, photosynthetic efficiency, and water relations, as well as adjustments in carbon allocation between vegetative and reproductive organs. At the molecular level, these responses are controlled by complex regulatory networks that modulate gene expression and stress adaptation [6–8]. Regulatory pathways involving stress-responsive transcription factors play a central role in coordinating these responses and maintaining plant resilience under adverse conditions [9–12]. Recent studies have highlighted the importance of such regulatory mechanisms in different plant species, including fruit crops, where stress-induced gene expression contributes to improved tolerance and recovery under challenging environmental conditions. Although these processes are increasingly well understood, their implications for applied crop management practices, particularly thermal treatments, remain insufficiently explored. A deeper integration of physiological and molecular knowledge into practical cultivation strategies may enable more precise steering of thermal treatments to optimize plant tolerance while minimizing stress-related damage.

Among the key pests affecting berry production, herbivorous mites are particularly problematic, causing substantial yield and quality losses in both strawberry and raspberry [13]. These organisms feed on plant tissues, leading to discoloration, reduced photosynthetic capacity, and ultimately lower fruit quality [13]. Although synthetic acaricides have traditionally been used for control, concerns regarding environmental impact, human health, and the development of resistant mite populations have driven the search for alternative strategies. In addition, regulatory restrictions on pesticide use further emphasize the need for non-chemical approaches that are compatible with sustainable production systems. Improved knowledge of pest and disease biology, including their sensitivity to environmental conditions, may also support the development of targeted control strategies based on physical treatments such as heat.

Heat-based treatments have long been employed in agriculture as non-chemical pest control methods [14–16]. Techniques such as hot air, steam, hot water immersion, and irradiation aim to raise plant tissue temperatures to levels lethal to pests while minimizing damage to the host plant. Among these, hot water treatment (HWT) involves immersing plant material in heated water for a defined period and is widely used for the sanitation of planting material. Its efficacy has been demonstrated against several pests and pathogens in berry crops, including phytopathogenic nematodes (primarily *Aphelenchoides fragariae*) [17], *Candidatus Phytoplasma rubi* [18], and mites such as *Tetranychus urticae* and *Phytonemus pallidus* [19,20]. However, the application of HWT inherently exposes plants to thermal stress, and the balance between pest control efficacy and plant tolerance remains a critical challenge. Optimizing this balance is particularly relevant for commercial production systems, where treatment precision and operational efficiency directly influence economic viability.

Despite these promising applications, the optimization of HWT parameters—particularly temperature and exposure duration—remains insufficiently explored for many berry crops. While excessive temperatures can impair plant growth and development, moderate thermal exposure may be tolerated depending on species, developmental stage, and environmental conditions. A better understanding of plant responses to controlled thermal treatments is therefore essential to define safe operational thresholds that ensure plant performance is not compromised while maintaining the potential for effective sanitation. Such knowledge could support the development of standardized protocols adapted to specific cultivars and production systems, thereby improving the reliability and adoption of HWT in practice.

Therefore, the aim of this study was to evaluate the effects of different HWT protocols on strawberry and raspberry plants under protected cultivation conditions. By testing a range of temperature–time combinations, we sought to identify treatment conditions that are well tolerated by the plants without compromising their performance. This work provides a basis for defining safe operational thresholds for HWT and supports its future integration into sustainable berry production systems. Ultimately, this approach may contribute to the development of economically viable and environmentally friendly alternatives to conventional plant protection strategies.

2. Materials and Methods

2.1. Experimental Setup for the Strawberry Experiment

The trial was conducted from June to November 2024 in Valais, Switzerland. Strawberry tray plants (Fragaria × ananassa, 'AuroraKarima') were cultivated in 8 L substrate pots (Beekenkamp Verpakkingen, Maasdijk, The Netherlands) under six plastic rain shelters (3.0 × 6.0 m each). On 21 June 2024, the tray plants were treated immediately prior to planting. Four treatments were evaluated: (i) ambient water temperature (18–20 °C, AT), (ii) 37 °C, (iii) 47 °C, and (iv) an untreated control. Water-treated plants were immersed for 10 min at the specified temperature using a HWT unit (Vititec, Donzère, France), following principles described for thermal pest control in horticultural crops [14,16]. Each treatment included 60 plants arranged in four plots (15 plants per plot). Planting density was 10 plants per linear metre, with 3.30 m between rows. The plants were irrigated and fertilized using a drip irrigation system.

2.2. Experimental Setup for the Raspberry Experiment

The trial was conducted from July to November 2024 in Valais, Switzerland. Raspberry plants (*Rubus idaeus*, 'Tulameen') were grown in substrate pots under a plastic tunnel (9.5 × 22.1 m). On 26 June 2024, the canes were removed from cold storage and held at room temperature for 24 h. The treatments were applied on 27 June 2024, and plants were established on 1 July 2024. Six treatments were tested: (i) AT (18–20 °C) for 60 min, (ii) 40 °C for 10 min, (iii) 40 °C for 60 min, (iv) 45 °C for 10 min, (v) 45 °C for 60 min, and (vi) an untreated control. Water-treated plants were immersed using the same HWT unit as described above. Each treatment comprised 64 canes arranged in eight plots (four pots per plot, two canes per pot). Planting density was three pots per linear metre, with 1.70 m between rows. Plants were irrigated and fertilized using a drip irrigation system.

2.3. Data Collection

2.3.1. Strawberry Experiment

To assess treatment effects on yield potential, the number of flowering stems per plant and the number of flowers per stem were recorded on four plants per plot on 24 July and 3 September 2024. Harvesting was conducted three times per week (Monday, Wednesday, Friday) from 26 July to 8 November 2024. At each harvest, all ripe fruits per plot were

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collected, sorted into marketable and non-marketable categories, and weighed. Average fruit weight per plot was determined by weighing a subsample of marketable fruits and dividing the total weight by the number of fruits in the subsample.

2.3.2. Raspberry Experiment

To assess initial infestation levels, gall mites were sampled on 27 June 2024 prior to treatment. From 20 plants, three buds per cane were excised and immersed in 70% ethanol for at least 30 min. Mites were extracted by filtration using cellulose nitrate membrane filters (0.8 µm pore size, 47 mm diameter; Göttingen, Sartorius) and counted under a stereomicroscope, following standard extraction procedures for small arthropods. Bud break was assessed on two canes per plot. Closed buds were counted at the time of sampling, and open buds were counted 14 days later. Bud break (%) was calculated as the proportion of open buds relative to the initial number of closed buds. Total leaf area per cane was measured at the end of the harvest period using a leaf area meter (LI-3100C, LI-COR, Lincoln, Nebraska USA), a widely used method for quantifying plant growth and canopy development. Harvesting was conducted three times per week from 4 September to 15 November 2024. At each harvest, all ripe fruits per plot were collected, sorted, and weighed. Average fruit weight per plot was calculated as described for strawberry.

2.4. Statistical Analysis

The effects of HWT on the raspberry and strawberry cumulative yield and fruit weight as well as the raspberry leaf surface area were analyzed separately with a one-way ANOVA, with HWT as the independent variable. The ANOVA model assumptions, namely homogeneity of the variance and normality of the residuals were verified by visual inspection of the normalized residuals, plotted against the fitted values, treatment levels, and QQ plots. If the graphical displays indicated a departure from these assumptions, further tests were performed on the model residuals using Breusch–Pagan and Bartlett test of homogeneity to assess homogeneity across the fitted values and across the treatments, respectively. To verify the normality of the residuals, we performed a Shapiro–Wilk test.

The numbers of strawberry flowering stems and flowers per plant were analyzed at each date of measurement (i.e., 24 July 2024 and 3 September 2024). The strawberry cultivar used in this experiment is ever-bearing; therefore, the temporal correlation in the response variables (i.e., number of flowering stems and number of flowers) was not of primary interest. Four generalized linear mixed models (GLMMs) assuming a Poisson distribution and log link were performed. The treatment and blocks were treated as fixed and random intercept variable, respectively. Overdispersion was tested and found significant for the number of flowers per plant at both dates ($\sigma^2 > \mu$). Thus, for the number of flowers per plant a GLMMs assuming a negative binomial was applied to correct for it. For GLMMs, homogeneity of the variance and normality of the Pearson residuals were assessed graphically against treatments, fitted values and QQ plots. Additionally, the random intercept QQ plots were visually inspected to verify the normality assumption of the random factor.

The proportion of raspberry bud breaks was analyzed with a GLMM assuming a beta-binomial distribution to correct for the overdispersion of the binomial GLMM. As beta-binomial distribution cannot compute 0 or 100% successes, we adjusted the proportion of bud breaks by removing 0.01% from all 100% success observations. Because beta-binomial model residuals are complex to interpret, we used the DHARMa package, for model residual diagnostics, to assess the model validity (i.e., homogeneity of variance and dispersion and normality of the model residuals).

All statistical analysis were performed in R (version 4.4.3). The one-way ANOVA models were performed in base R, the GLMMs with Poisson, negative binomial and beta-binomial distributions were performed with lme4 [21], MASS [22], and glmmTMB packages [23], respectively. For the beta-binomial GLMM residual assessment, we used DHARMa [24]. The post hoc analysis was performed with emmeans [25]. The figures were made using the GGplot2, RColorBrewer, colorspace, and patchwork packages [26–29]).

3. Results

3.1. Pest Infestation Prior to Treatment

The initial gall mite infestation levels were extremely low prior to treatment, with only eight gall mites detected on four of the 20 sampled plants. No spider mites were observed. Consequently, the effect of HWT on mite reduction could not be reliably assessed.

3.2. Vegetative Growth and Flower Development

No significant difference was observed in the development of strawberry fruit-bearing organs between different treatments and the two sampling dates (Figures 1 and 2). However, the impact of HWT on the first measurement date appears to be greater than during the second flowering cycle of the plants (Figure 2). The control treatment produced the highest number of flowering stems, with an average of 7.1 (±0.64) per plant, but also a higher number of flowers, with an average of 30.0 (±2.40) flowers per plant on 24 July. Conversely, the increase in temperature seemed to have had a negative impact on both parameters, with a decrease in the average number of flowering stems and flowers per plant as the treatment temperature increased. Plants treated at 47 °C had the lowest average number of flowering stems, with only 4.9 (±0.36) per plant, but also fewer flowers, with 21.6 (±1.67) flowers observed per plant. Treatment with water at AT had the same effect on the development of strawberry fruit-bearing organs as treatment at 37 °C with 5.9 (±0.68) and 6.0 (±0.72) flowering stems per plant and 25.2 (±2.88) and 26.3 (±2.93) flowers per plant, respectively.

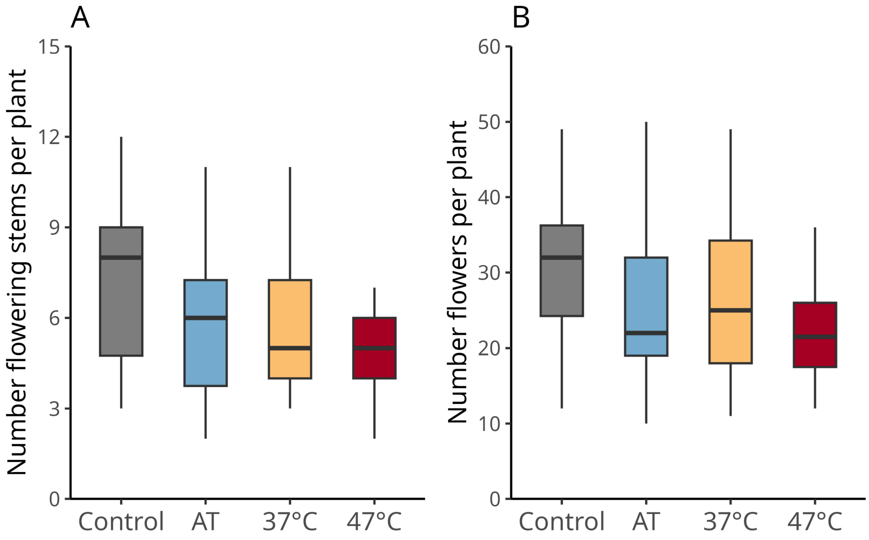

Figure 1. Effect of hot water treatments (HWTs) on (**A**) the number of flowering stems per strawberry plant and (**B**) the number of flowers per plant at the first sampling on 24 July 2024. Treatments included control (no treatment), ambient water temperature (18–20 °C, AT), 37 °C, and 47 °C applied for 10 min prior to planting.

In contrast, measurements taken during the second production cycle on 3 September showed much smaller differences between the control and the treatments, with similar average numbers of flowering stems and flowers per plant. HWT at 47 °C produced the lowest number of flowering stems per plant, with an average of 4.8 (±0.36) per plant, compared to 5.3 (±0.34) for the control, which had the highest average. However, the average number of flowers was the lowest for the latter, with 26.7 (±2.76) flowers produced per strawberry plant, while the treatment at 37 °C had the highest average with 28.6 (±2.79) flowers per plant.

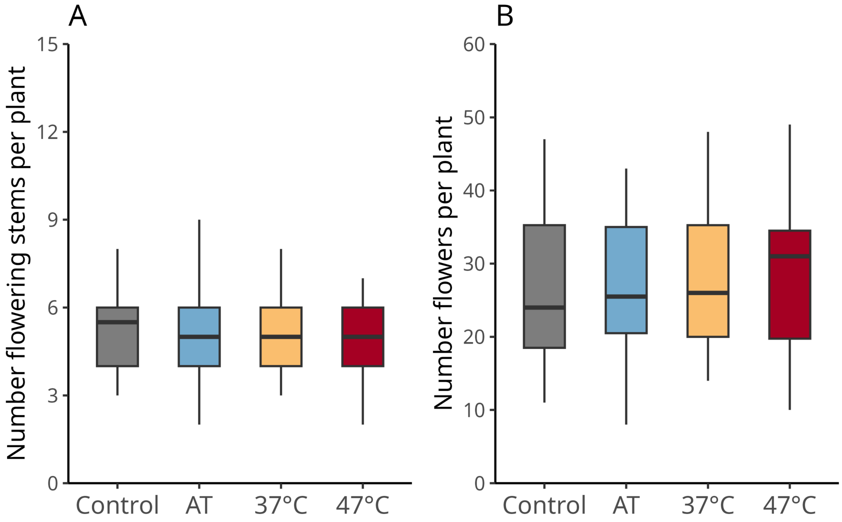

Figure 2. Effect of hot water treatments (HWTs) on (**A**) the number of flowering stems per strawberry plant and (**B**) the number of flowers per plant at the second sampling on 3 September 2024. Treatments included control (no treatment), ambient water temperature (18–20 °C, AT), 37 °C, and 47 °C applied for 10 min prior to planting.

For raspberries, bud break was significantly influenced by HWTs. Except in the 10 min HWT at 40 °C, plants treated with hot and AT water showed reduced bud break compared to the control (Figure 3). The percentage of bud break decreased with increasing treatment temperature and duration, resulting in the strongest reduction in the 60 min HWT at 45 °C. While water treatment at AT reduced bud break compared to the control, 10 min HWT at 40 °C gave intermediate results, no different from the control. Average leaf area was similar among all groups. However, greater variability was observed on plants treated with hot and AT water (Figure 4).

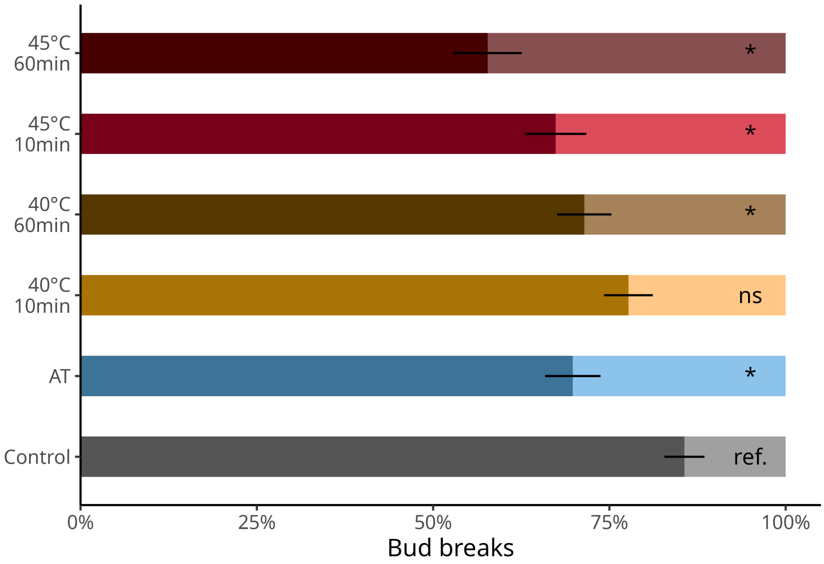

Figure 3. Effect of hot water treatments (HWTs) on bud break (%) of raspberry canes. Treatments included control (no treatment), ambient water temperature (18–20 °C, AT, 60 min), 40 °C (10 and 60 min), and 45 °C (10 and 60 min). Bars represent mean values ± standard error (SE). * indicates significant differences from the control (ref.) (GLMM, $p < 0.05$), ns = non-significant.

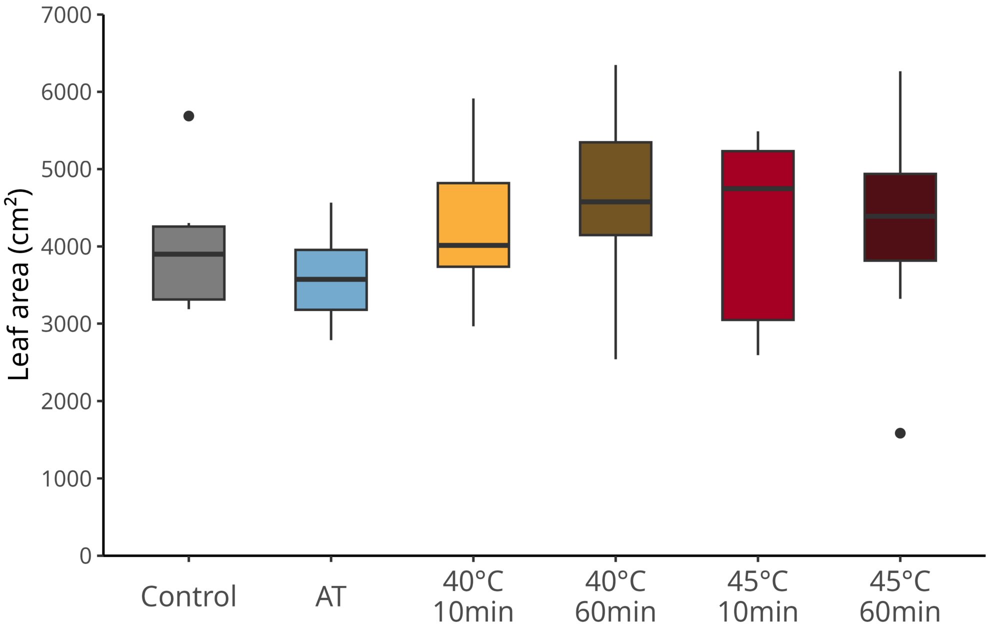

Figure 4. Effect of hot water treatments (HWTs) on total leaf area per raspberry cane at the end of the harvesting period. Treatments included control (no treatment), ambient water temperature (18–20 °C, AT, 60 min), 40 °C (10 and 60 min), and 45 °C (10 and 60 min). Black dots beyond the whiskers indicate outliers.

3.3. Crop Yield and Fruit Weight

A decrease in marketable strawberry yield per plant is observed for all HWTs, compared with the control, although the differences are not significant (Figure 5). With a production of approximately 337 g per plant, the 47 °C HWT had the lowest production, compared with approximately 374 g per plant for the control zone. Plants treated with 37 °C hot water and those at AT had intermediate results, with approximately 350 g and 358 g of fruit harvested per plant, respectively.

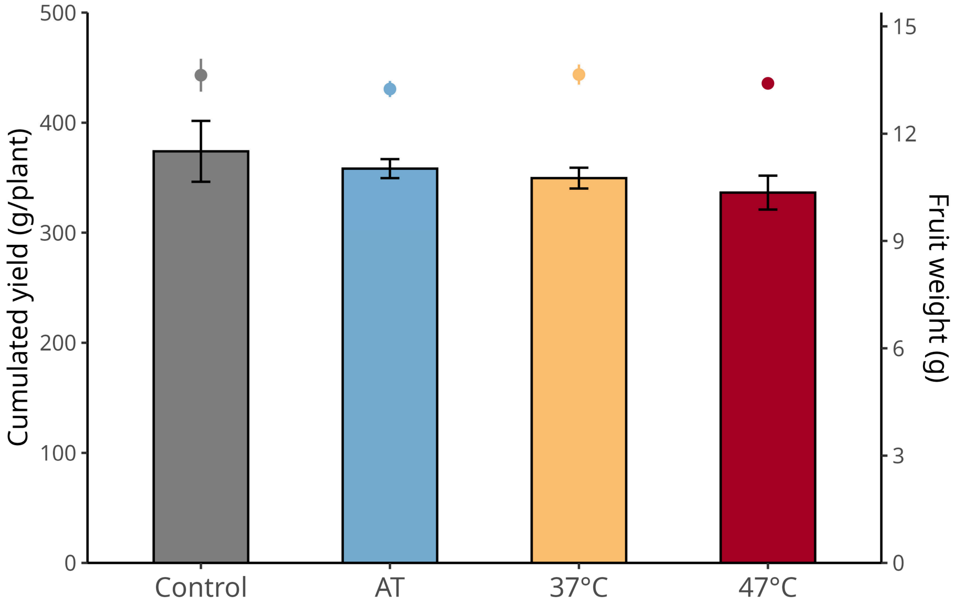

Figure 5. Effect of hot water treatments (HWTs) on marketable yield (g per plant, coloured bars with primary axis) and average fruit weight (g, coloured dots with secondary axis) in strawberry. Treatments included control (no treatment), ambient water temperature (18–20 °C, AT), 37 °C, and 47 °C applied for 10 min prior to planting.

As for the yields, average strawberry fruit weights were not significantly affected by HWTs. Plants treated with AT had the lowest average weights per fruit (13.25 + 0.45 g). The HWT at 37 °C resulted in a similar average fruit weight to the control, with 13.65 (±0.56) g per fruit, compared to 13.64 (±0.92) g. Finally, the highest treatment temperature had no significant impact on the average fruit weight, which was 13.41 (±0.32) g.

Marketable raspberry yield tended to be lower in all water treatments compared to the control, although the differences were non-significant (Figure 6). Treatment duration appeared to affect yield more than temperature. The control plants produced the most marketable raspberries, followed by those treated at AT and at 40 °C and 45 °C for 10 min. Raspberry plants treated at 40 °C and 45 °C for 60 min had the lowest yield.

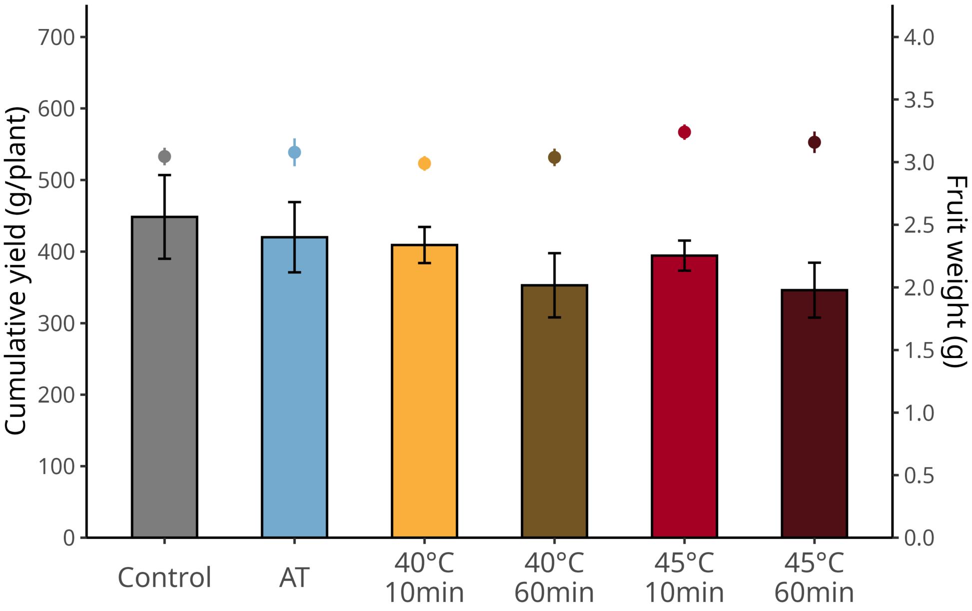

Figure 6. Effect of hot water treatments (HWTs) on marketable yield (g per plant, coloured bars with primary axis) and average fruit weight (g, coloured dots with secondary axis) in raspberry. Treatments included control (no treatment), ambient water temperature (18–20 °C, AT, 60 min), 40 °C (10 and 60 min), and 45 °C (10 and 60 min).

No significant effect of the HWTs was measured on raspberry fruit weight. However, raspberries tended to be lighter in the control group and after the water treatment at AT than in the 45 °C HWTs (Figure 6).

4. Discussion

This study evaluated the physiological and productive responses of strawberry and raspberry plants to HWT, a non-chemical pest management approach increasingly considered for sustainable and residue-free production systems. Overall, both crops showed a high level of tolerance to the tested HWT protocols, although species-specific responses were observed, particularly during early developmental stages.

4.1. Vegetative Growth and Bud Development

In strawberry, HWTs up to 47 °C for 10 min did not significantly affect vegetative development, as reflected by the similar number of flowering stems and flowers across treatments. This indicates that strawberry tray plants can tolerate short-duration thermal exposure without impairing reproductive initiation. These findings are consistent with previous studies showing that moderate heat treatments can be applied without compromising plant development or pest control efficacy [14,16,19,20].

In contrast, raspberry plants exhibited a clear sensitivity to higher treatment temperatures, with significantly reduced bud break. This effect was not reflected in leaf area or later developmental stages, suggesting that dormant buds are particularly vulnerable to thermal stress. Similar effects of heat on bud physiology have been reported in raspberry and other woody species, where HWT can disrupt dormancy release and reduce subsequent growth [6–8]. More generally, near-lethal heat stress has been shown to interfere with bud break processes through physiological and molecular changes, including stress protein induction and metabolic disruption [30–32]. Reduced bud break may therefore compromise crop establishment and uniformity, particularly in production systems where early growth is critical.

4.2. Yield and Fruit Weight

Yield responses further highlight differences between the two species. In strawberry, all HWTs showed a tendency toward reduced yield compared with the control, with the strongest reduction observed at 47 °C. Although these differences were not statistically significant, the consistent trend suggests that higher temperatures may induce sublethal stress affecting fruit development. Heat treatments are known to influence physiological processes such as carbohydrate metabolism and water relations, which may indirectly affect fruit set and growth [4,5]. As flowering parameters were not significantly altered, these effects likely occur during or after fruit set.

In raspberry, neither cumulative yield nor average fruit weight was significantly affected by HWT, even at higher temperatures and longer exposure durations. This suggests that, once bud break has occurred, raspberry plants can compensate for early stress and maintain productivity. The use of dormant planting material may contribute to this resilience, as physiological activity is limited during treatment, reducing susceptibility to heat-induced damage [4,5].

4.3. Implications for HWT in Berry Production

The results of this study provide practical insights into the integration of HWT into berry production systems. In strawberry, treatments up to 37 °C appear to represent a suitable compromise, minimizing potential negative effects on yield while still offering the possibility of pest suppression. The demonstrated efficacy of HWT against key pests such as *Tetranychus urticae* and *Phytonemus pallidus* supports its potential use in integrated pest management strategies [14–16].

In raspberry, HWT can be applied at higher temperatures and longer durations without affecting yield or fruit size, provided that bud viability is preserved. The reduction in bud break at elevated temperatures emphasizes the importance of defining safe treatment thresholds, particularly when treating dormant planting material. This is especially relevant for sanitation strategies targeting pathogens and pests such as phytoplasmas or nematodes, for which HWT has already shown promising results [17–20].

4.4. Limitations and Future Directions

A key limitation of this study is low pest pressure, meaning that the efficacy of HWT in controlling target organisms was not assessed. Previous studies have demonstrated the potential of HWT for controlling a wide range of pests and pathogens [4,5], but its effectiveness under commercial berry production conditions remains to be validated.

Future research should therefore include infested plant material to quantify pest control efficacy under realistic conditions. In addition, as this study was conducted on a single cultivar per species and during a single production season, the results should be interpreted with caution and require validation across a broader range of genotypes and environmental conditions. Integrating physiological and molecular indicators of stress responses would further improve understanding of plant tolerance mechanisms. Finally, evaluating postharvest quality will be essential to determine the overall impact of HWT on fruit marketability.

5. Conclusions

This study evaluated the effects of HWT on plant performance, bud break, and yield in strawberry and raspberry under protected cultivation conditions. The results indicate that both species exhibit a generally high tolerance to short-duration HWT, although responses vary depending on species and developmental stage. In strawberry, treatments up to 37 °C did not negatively affect vegetative development or yield, while higher temperatures (47 °C) showed a tendency to reduce yield. In raspberry, higher temperatures significantly reduced bud break, highlighting a sensitivity during early developmental stages, although no significant effects on yield or fruit weight were observed once plants were established. These findings suggest that HWT can be applied within defined temperature thresholds without compromising plant performance, providing useful guidance for its potential integration into berry production systems. However, as this study was conducted on a single cultivar per species and during a single production season, the results should be considered as preliminary and require validation across a wider range of genotypes and environmental conditions. Furthermore, due to the absence of pest pressure, no conclusions can be drawn regarding the efficacy of HWT for pest or pathogen control in the present study. Future research should therefore combine assessment of plant tolerance with direct evaluations of pest suppression under realistic production conditions. Overall, this study provides a foundation for optimizing HWT protocols in berry crops, contributing to the development of sustainable and non-chemical crop management strategies.

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