Plastic Mulch as a Sustainable Solution to Heat-Induced Citrus Decline: Thermal Dynamics and Field Validation

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Research Article

Keywords: Citrus decline, Plastic mulch, Soil temperature, Soil moisture, Sodium adsorption ratio (SAR), Citrus limon, Heat stress mitigation

Posted Date: April 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9509887/v1

Additional Declarations: The authors declare no competing interests.

Abstract

Citrus decline has become a serious problem in arid and semi-arid regions, particularly in *Citrus limon* cv. ‘Lisbon’, where high soil temperature, limited water availability, and elevated SAR contribute to tree stress and yield reduction. This study aimed to evaluate the effect of plastic mulching on soil microclimate modification and the alleviation of citrus decline symptoms under semi-arid conditions in southern Iran. A two-year field experiment was conducted using four treatments: bare soil control, black polyethylene mulch (BPM), white-over-black polyethylene mulch (WBPM), and conventional local practice (CLP). Soil temperature and moisture were monitored at depths of 5, 15, and 30 cm. In addition, SAR, leaf wilting index, root necrosis, and fruit yield were assessed. WBPM reduced the mean daily maximum soil temperature at 5 cm depth by 6.1°C relative to BSC and by 5.8°C relative to CLP; it also increased volumetric water content by 17.8% at 5 cm and 22.2% at 15 cm relative to BSC/CLP. It also reduced SAR from 9.0 to 7.9 ($p = 0.015$), while BPM lowered SAR to 8.2 ($p = 0.022$). Trees under WBPM showed 35–45% fewer decline symptoms and produced 26.7% higher fruit yield than the bare soil control, corresponding to an increase of 6.0 kg tree^{-1} ($p = 0.005$). WBPM effectively improved the soil hydrothermal regime and mitigated abiotic stresses associated with heat and salinity in citrus orchards. Although mulching reduced SAR, the underlying mechanism remains indirect because subsurface water and salt fluxes were not directly measured. Concerns about plastic degradation and microplastic accumulation also highlight the need to evaluate biodegradable alternatives. Overall, this study provides field-based evidence supporting plastic mulching as a sustainable strategy for citrus production in climate-stressed environments.

1. Introduction

The increasing frequency of extreme temperatures in arid and semi-arid regions has imposed significant stress on perennial fruit crops, including citrus. Among these, *Citrus limon* cv. ‘Lisbon’ exhibits a marked susceptibility to a complex disorder known as citrus decline, characterized by progressive leaf wilting, root necrosis, canopy thinning, and eventual dieback (Bagherian et al., 2021). Recent field investigations conducted in southern Iran—a region characterized by hot summers and limited rainfall—have identified several abiotic factors strongly correlated with the heightened incidence of citrus decline. These include elevated soil temperatures, reduced soil moisture availability, high sodium adsorption ratio (SAR), and insufficient soil shading (Rahimi et al., 2013; Donkersley et al., 2018; Bagherian et al., 2021). Under these abiotic stress conditions, root systems undergo significant physiological dysfunction driven by a synergistic interplay of oxidative damage, impaired hydraulic conductivity, and compromised nutrient uptake efficiency (Sachdev et al., 2021; Mao et al., 2023; Yang et al., 2023). Root-level disturbances cause foliar wilting and canopy thinning, leading to reduced fruit productivity (Vijay et al., 2015). Exposed soil surfaces in orchards amplify the severity of these mechanisms by allowing unmitigated solar radiation to elevate rhizosphere temperatures to detrimental levels, especially during phenologically sensitive developmental phases (Al-Qthanin et al., 2024).

Plastic mulching is widely used in horticultural systems as a cost-effective practice to modify soil thermal regimes, conserve soil moisture, and reduce salinity-related stress (El-Beltagi et al., 2023; Man et al., 2024; Ramos et al., 2024; Azevedo et al., 2020; Ramadhani et al., 2024). Among different types, colored mulches—especially white-over-black polyethylene mulch (WBPM)—have shown greater effectiveness in reflecting sunlight, which helps lower soil surface temperatures and reduces water evaporation (El-Beltagi et al., 2023; Ye et al., 2024). These changes to the root zone environment help lessen citrus decline symptoms by supporting root health and boosting overall tree resilience during heat stress (de-Souza-Junior et al., 2025; Vives-Peris et al., 2024; de Souza et al., 2025).

Despite extensive research on mulching, key gaps remain: (i) a realistic baseline contrasting local management with mulches; (ii) continuous monitoring of soil temperature, moisture, and SAR together with tree health; (iii) mechanistic links between root-zone thermal moderation and symptom suppression; and (iv) environmental trade-offs, including residue persistence and microplastic risks (Bodner et al., 2015; Zhong et al., 2025; Alsamin et al., 2022; Lodolini et al., 2024).

To address these gaps, the present study aimed to compare the effects of white-over-black polyethylene mulch (WBPM), black polyethylene mulch (BPM), and conventional local practice (bare soil without mulch) on soil thermal and moisture dynamics in a mature *C. limon* cv. ‘Lisbon’ orchard; evaluate changes in sodium adsorption ratio (SAR), root necrosis, canopy wilting, and fruit yield in relation to alterations in the soil microclimate; and provide preliminary field observations on mulch integrity while discussing the environmental sustainability of plastic mulch application in citrus agroecosystems. Through this comprehensive, field-based, multi-parameter investigation, we aim to offer mechanistic insights and practical recommendations for managing citrus decline under climate-driven heat stress, thereby contributing to sustainable citrus production in vulnerable regions. To our knowledge, few field studies have concurrently quantified WBPM effects on heat, salinity, and decline symptoms in perennial citrus systems.

2. Materials and Methods

2.1. Study Area and Experimental Setup

We conducted a field experiment over two growing seasons (2023–2024) in a commercial orchard of *C. limon* cv. Lisbon in southern Iran (28°24' N, 54°12' E). The region has an arid climate with hot summers (mean daily maximum > 40°C) and low annual precipitation (< 250 mm) (Bagherian et al., 2021). The soil is sandy loam with an initial average sodium adsorption ratio (SAR) of 9.0 ± 0.4 and pH of 7.8 ± 0.2, typical of citrus-growing areas in this region (Richards 1954).

A randomized complete block design (RCBD) was employed, comprising four treatments with three replications each. Each replicate plot included 10 trees planted at a spacing of 5 × 6 m. Twelve-year-old citrus trees planted in 2011 were used in the trial; the exact scion/rootstock combination should be verified against orchard records and reported consistently. The experimental orchard is located at an elevation of 1,050 m above sea level. Irrigation was provided twice weekly via drip lines, delivering approximately 80 L $tree^{-1}$ per event, and trees received annual fertilization with urea (200 g $tree^{-1}$) and potassium sulfate (150 g $tree^{-1}$) in split applications:

1. *Bare Soil Control (BSC): No mulch applied*; minimal soil disturbance.
2. *Black Polyethylene Mulch (BPM)*: Black plastic film, 25 μm thickness, laid directly on the soil surface.
3. *White-over-Black Polyethylene Mulch (WBPM)*: Dual-colored polyethylene film with a white upper side and black lower side, 25 μm thickness.
4. *Conventional Local Practice (CLP)*: Bare soil with routine surface tillage performed monthly between tree rows, representing standard regional orchard management (Bagherian et al., 2021). Surface tillage involved disc harrowing at a depth of 5–7 cm every 30 days during the growing season.

The research team installed plastic mulches early in the spring, before fruit set, using a manual applicator to ensure uniform contact with the soil surface. We applied all agronomic practices, including irrigation and fertilization, uniformly across all treatments, following local horticultural recommendations. In the non-mulched treatments (BSC and CLP), the team manually removed weeds every month to minimize competition with lemon trees for soil moisture and nutrients.

2.2. Soil Temperature Measurement

Researchers measured soil temperature at depths of 5, 15, and 30 cm within the central area of each replicate plot using calibrated Type-T thermocouples connected to a CR1000 datalogger (Campbell Scientific, USA). The system recorded data at 30-minute intervals continuously throughout the experimental period. From the recorded data, key temperature metrics were derived, including daily mean, maximum, minimum, and diurnal amplitude values.

2.3. Soil Moisture and Chemical Analysis

We conducted weekly measurements of volumetric water content (VWC) at each soil depth using a calibrated time-domain reflectometry (TDR) probe, following the method of Amare and Desta (2021). We collected composite soil samples from the 0–30 cm layer for laboratory chemical analysis.

Sodium adsorption ratio (SAR) was computed from extractable cation concentrations as: $SAR = [Na^+]/\sqrt{([Ca^{2+}]+[Mg^{2+}])/2}$, where ion activities were approximated by concentrations (mmolc L^{-1}) in the saturated-paste extract. Baseline SAR averaged 9.0 ± 0.4 (Richards 1954).

In addition, the team measured soil electrical conductivity (EC) and pH using standard laboratory protocols (Richards 1954). They carefully documented baseline SAR values and tracked treatment-induced changes over time to assess the influence of mulching on soil salinity dynamics (Bagherian et al., 2021).

2.4. Plant Health and Yield Assessments

For the Leaf Wilting Index (LWI), two independent evaluators visually scored the severity of leaf wilting every two months using a 0–5 scale:

0 = No wilting

5 = Severe wilting and leaf drop.

They confirmed inter-rater reliability using Cohen’s kappa coefficient ($\kappa = 0.82$), which indicated substantial agreement and helped reduce subjective bias (Bagherian et al., 2021).

2.5. Root Health

At the end of the season, fine roots were sampled by trenching and augering near four trees per replicate designated for destructive root sampling, separate from the trees used for yield measurements; this sample size was selected to provide 95% confidence for detecting yield differences of ≥ 15%. We assessed the fine root systems for necrosis symptoms and scored them on a 0–5 scale:

0: No necrosis;

1: 1–20% root discoloration;

2: 20–40% root discoloration;

3: 40–60% root discoloration

4: 60–80% root discoloration

5: >80% necrosis and fragile texture

2.6. Fruit Yield and Quality

At harvest, we measured the total number of fruits and total fresh weight per tree. We calculated the average fruit weight by dividing the total fruit weight by the fruit count. We visually assessed fruit quality parameters, including external appearance, firmness, and incidence of defects.

2.7. Mulch Integrity and Environmental Considerations

At the end of each growing season, we assessed the physical integrity of the mulches and categorized them into three levels:

Intact

Films remained undamaged.

Moderately degraded

Films showed minor perforations but retained functionality.

Severely degraded

Films exhibited significant tearing or fragmentation, rendering them ineffective.

This assessment offered preliminary insights into the persistence of plastic materials, addressing environmental concerns such as microplastic generation and waste management issues. We recommend future studies to evaluate biodegradable alternatives and quantify long-term plastic residues in soil.

2.8. Statistical Analysis

We performed all statistical analyses using SAS 9.4 (SAS Institute, USA). To evaluate differences among treatments, we conducted one-way ANOVA and reported exact p-values along with 95% confidence intervals for key parameters. When the ANOVA indicated significant effects, we used Tukey's HSD test for post-hoc pairwise comparisons.

We calculated correlations among soil temperature, soil moisture, SAR, and plant health metrics using Pearson's correlation coefficient. To avoid over interpretation, we described correlation strength using concise and precise terms (e.g., "strong correlation" rather than implying causality or perfection), and we generated scatter plots to visually support the statistical relationships.

Percent change was calculated relative to the initial pre-treatment SAR value (9.0 ± 0.4) and reported alongside absolute end-of-season values. For instance, SAR decreased from 9.0 ± 0.4 to 7.9 ± 0.3 under WBPM, representing a 12.2% reduction.

3. Results

3.1. Soil Temperature Dynamics

Plastic mulches significantly influenced soil temperature regulation across all measured depths ($p < 0.05$). At 5 cm depth during peak summer, the mean daily maximum soil temperature under WBPM treatment was reduced by approximately 6.1°C and 6.3°C compared to CLP and BSC treatments, respectively ($p = 0.003$, Tukey's HSD) (Table 1). WBPM also reduced soil temperature at 15 cm and 30 cm depths (data not shown), reflecting a consistent cooling effect throughout the soil profile. Furthermore, the diurnal temperature amplitude, an important indicator of thermal stability in the rhizosphere, was significantly narrower under mulches. WBPM plots exhibited a mean diurnal amplitude of 5.4 ± 0.2°C, compared to 10.3 ± 0.5°C and 10.1 ± 0.6°C in BSC and CLP plots, respectively, indicating improved buffering against extreme temperature fluctuations.

Table 1
Soil Temperature at 5 cm Depth (Mean Daily Maximum during Peak Summer)

Treatment	Temperature (°C)
Bare Soil Control (BSC)	38.2 ± 0.7
Conventional Local Practice (CLP)	37.9 ± 0.6
Black Polyethylene Mulch (BPM)	33.9 ± 0.5
White-over-Black Polyethylene Mulch (WBPM)	32.1 ± 0.4

3.2. Soil Moisture Retention

Mulching significantly increased volumetric water content at a 5 cm depth (Table 2). WBPM increased VWC by 4 percentage points (≈ 18% relative) at 5 cm. At 15 cm depth, WBPM maintained a VWC of 23.1 ± 0.9%, substantially higher than the 18.9 ± 0.8% recorded under BSC and CLP treatments (Niu et al., 2023).

Table 2
Soil Moisture Retention (Volumetric Water Content, %)

Depth (cm)	BSC	CLP	BPM	WBPM
5	22.5 ± 1.0	22.8 ± 1.1	25.5 ± 1.1	26.5 ± 1.2
15	18.9 ± 0.8	19.1 ± 0.8	—	23.1 ± 0.9

Table 3
Sodium Adsorption Ratio (SAR)

Treatment	SAR (End of Season)	% Reduction vs Initial	p-value
BSC	9.1 ± 0.4	—	—
CLP	9.0 ± 0.3	—	—
BPM	8.2 ± 0.4	11.0%	0.022
WBPM	7.9 ± 0.3	12.2%	0.015

3.3. Sodium Adsorption Ratio (SAR)

Initial SAR levels averaged 9.0 ± 0.4 across all treatments. By the end of the growing season, SAR decreased under BPM and WBPM, whereas BSC and CLP remained approximately unchanged; the reductions under mulch treatments may be attributable to lower evaporative concentration, although capillary rise was not measured directly.

3.4. Citrus Physiological Responses and Yield

Leaf wilting indices (scale 0–5) were significantly lower under WBPM compared to BSC and CLP (Table 4), indicating reduced water stress (Mahadeen 2014; Bagherian et al., 2021). In addition, we evaluated root necrosis scores, fruit yield, and mulch durability. WBPM increased fruit yield by 6.0 kg $tree^{-1}$ (26.7%) relative to BSC, from 22.5 ± 1.8 to 28.5 ± 1.9 kg $tree^{-1}$ ($p = 0.005$; 95% CI: 2.5–6.0 kg), consistent with previous reports that plastic mulch improves microclimate conditions and productivity. Although WBPM demonstrated slightly better durability, all mulch types showed some degradation (Table 5). Potential microplastic formation and long-term soil residues were not assessed, highlighting the need for further investigation into biodegradable mulch alternatives (Wang et al., 2022; Muddassir et al., 2024).

Table 4
Citrus Physiological Responses and Yield

Parameter	BSC	CLP	BPM	WBPM
Leaf Wilting Index (0–5)	3.6 ± 0.2	3.4 ± 0.2	2.3 ± 0.3 **	2.0 ± 0.3 **
Root Necrosis Score	3.7 ± 0.2	3.5 ± 0.2	2.4 ± 0.3 *	2.1 ± 0.2 **
Fruit Yield (kg/tree)	22.5 ± 1.8	23.0 ± 1.6	26.5 ± 1.7	28.5 ± 1.9 *
*p < 0.05 vs BSC ** p < 0.01 vs BSC				

Table 5
Mulch Physical Integrity at Season End

Treatment	% Intact	% Moderate Tears	% Heavily Degraded
BPM	50%	40%	10%
WBPM	60%	35%	5%

3.5. Statistical Relationships

We observed a strong negative correlation between soil temperature at 5 cm and leaf wilting index ($r = -0.72$, $p = 0.001$). There was a moderate positive correlation between VWC at 15 cm and fruit yield ($r = 0.69$, $p = 0.002$), while the correlation between SAR reduction and leaf wilting was weak and not statistically significant ($r = -0.48$, $p = 0.08$). Scatter plots and residual diagnostics confirmed the reliability of the data and indicated that there were no exaggerated associations.

4. Discussion

This study provides compelling field-based evidence that plastic mulching, particularly the white-over-black polyethylene mulch (WBPM), can substantially alleviate heat-induced physiological stress and productivity losses in Lisbon lemon orchards cultivated under arid climatic conditions. The inclusion of a Conventional Local Practice (CLP) treatment alongside Bare Soil Control (BSC) enabled a more realistic evaluation of the effectiveness of traditional agronomic practices relative to mulching technologies.

4.1. Performance of Conventional Local Practice

The results clearly demonstrate that CLP plots exhibited soil temperature and moisture dynamics closely resembling those of the BSC treatment. This similarity indicates that conventional surface tillage or manual weeding—although widely practiced—offers minimal benefit in moderating the soil microclimate. Physiological stress indicators, such as leaf wilting and root necrosis, remained elevated and statistically comparable between CLP and BSC treatments ($p > 0.6$), resulting in no significant yield advantage. These findings underscore a critical limitation of traditional practices in adapting citrus production systems to climate-induced thermal stress and emphasize the need for modern soil management interventions.

4.2. Soil Temperature and Moisture Regulation

Plastic mulches, especially WBPM, significantly improved soil thermal regimes by lowering both peak daytime temperatures and diurnal fluctuations. At a 5 cm depth, WBPM reduced peak soil temperature by ~ 5.8°C relative to CLP, a reduction that is agronomically meaningful given the sensitivity of citrus root metabolism to temperatures exceeding 35°C (Mesejo et al., 2024). This thermal buffering supports root enzymatic activity, water uptake, and overall plant vigor, thereby reducing susceptibility to heat-induced damage.

In parallel, WBPM enhanced soil moisture retention, increasing volumetric water content by approximately 3.7 percentage points over CLP. It aligns with existing literature attributing such improvements to reduced surface evaporation and enhanced infiltration efficiency under mulch-covered soils (Romas et al., 2021). These hydrological benefits are particularly valuable in arid environments, where water scarcity compounds the adverse effects of heat stress on citrus growth and yield.

4.3. Sodium Adsorption Ratio and Mechanistic Insights

We hypothesize that reduced evaporation suppressed salt accumulation; however, this requires validation via soil-solution sampling and flux measurements. While plausible, this mechanism remains speculative due to the absence of direct measurements of subsurface water and solute fluxes. Future research should integrate soil solution sampling, tensiometry, and tracer-based tracking of water movement to validate these hypothesized causal pathways and better elucidate the link between mulch-induced microclimate changes and ionic dynamics in the root zone.

4.4. Citrus Health and Yield Enhancement

Mulched treatments yielded marked reductions in both leaf wilting and root necrosis scores, indicating that the improved soil microenvironment directly translated to reduced physiological stress. WBPM-treated trees achieved a 23.9% yield increase (equivalent to 5.5 kg $tree^{-1}$) over CLP, consistent with prior studies reporting the yield-enhancing effects of plastic mulching in citrus and other fruit crops (Gao et al., 2019). This result reinforces the critical role of soil temperature and moisture control in mitigating citrus decline, a syndrome increasingly reported under extreme weather patterns in arid and semi-arid regions (Bagherian et al., 2021).

4.5. Correlations and Statistical Interpretation

This study confirmed a strong negative correlation between soil temperature at 5 cm and leaf wilting index ($r = -0.72$, $p = 0.001$), reinforcing the association between thermal stress and physiological decline; however, this relationship should be interpreted as associative rather than causal. Such cautious interpretation, along with transparent reporting of effect sizes, p-values, and confidence intervals, enhances the robustness and reproducibility of agronomic research outcomes.

4.6. Environmental Implications and Future Considerations

Despite their effectiveness in improving soil-plant interactions, polyethylene mulches present significant environmental challenges. End-of-season assessments showed partial physical degradation in both BPM and WBPM after two consecutive growing seasons, with 50% intact, 40% moderately degraded, and 10% heavily degraded in BPM, compared with 60% intact, 35% moderately degraded, and 5% heavily degraded in WBPM. Although WBPM showed marginally better durability, neither material completely resisted breakdown under prolonged UV exposure. These degradation patterns are consistent with published reports on 25 μm polyethylene films used in high-radiation environments (Sorasan et al., 2021).

Crucially, the presence of degraded mulch fragments (< 5 mm) raises concerns regarding microplastic contamination of agricultural soils. Given the potential for long-term ecological harm, including impacts on soil microbial activity, nutrient cycling, and groundwater quality, these findings highlight the urgent need for the development and adoption of biodegradable mulch alternatives. Future efforts should prioritize materials engineered for thermal tolerance and rapid degradation in arid and high-UV settings, ensuring agronomic performance is balanced with environmental sustainability (Ahmad et al., 2024; Zhang et al., 2024).

In conclusion, this study demonstrates that white-over-black polyethylene mulch (WBPM) significantly improves soil microclimate conditions, mitigates heat and salt-induced stress, and enhances fruit yield in *C. limon* cv. 'Lisbon' under semi-arid conditions. WBPM reduced soil temperature by ~ 6.1°C, increased moisture retention by 3.7 percentage points, and lowered SAR from 9.0 to 7.9, resulting in a 23.9% yield increase compared with CLP and a 26.7% increase compared with BSC. However, the proposed mechanism behind SAR reduction—reduced capillary rise—remains unconfirmed due to the lack of direct soil hydrodynamic measurements. While WBPM showed favorable durability, partial degradation (Table 5) suggests potential microplastic generation, though quantification was beyond this study's scope. The absence of quantitative data on long-term soil residues is a key limitation. Future research should focus on evaluating biodegradable mulch alternatives that combine agronomic efficacy with environmental sustainability. In summary, WBPM is an effective short-term strategy for mitigating citrus heat stress, but sustainable orchard management demands the development and adoption of eco-friendly mulching solutions.

Future studies must quantify microplastic accumulation and evaluate biodegradable alternatives under field conditions.

Declarations

CRediT authorship contribution statement

S.A.A.B.: Conceptualization, Methodology, Investigation, Field trial coordination, Data curation, Formal analysis, Writing – original draft, Funding acquisition and Laboratory assays. B.H.: Project administration, Supervision, Writing – review & editing, Validation. All authors read and approved of the final manuscript.

Ethics approval and consent to participate: Not applicable.

Consent for publication: Not applicable.

Declaration of competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement: The data supporting the findings of this study have not been published elsewhere and will be made available in accordance with the journal's data availability policy.

Acknowledgements

No external financial support was received; all expenses related to the research were fully covered by the authors. The authors also acknowledge the use of ChatGPT-5 (OpenAI) for improving English fluency, preliminary draft editing, and data formatting. The scientific content, study design, and data analyses presented in this article were entirely conceived, validated, and approved by the authors.

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