

Mulch-Mediated Enhancement of Physiological Performance and Macronutrient Status in Mandarin (*Citrus reticulata* Blanco) Cultivation Under Semi-Arid Vertisol Conditions

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Abstract

Purpose

This study investigated how organic versus synthetic mulching systems influence soil-plant water relations and nutrient dynamics in Nagpur mandarin through mechanistic evaluation of physiological responses and soil microbial activity in semi-arid conditions where water stress and nutrient deficiencies limit citrus productivity.

Methods

A randomized complete block design compared nine treatments over eight months: control, synthetic mulches (silver, black, transparent polythene, Weedmat), and organic mulches (mustard straw, coriander straw, jamun leaves, soybean straw). Parameters measured included soil water-holding capacity, plant water status, gas exchange, stress indicators, leaf macronutrients (N, P, K), and soil microbial populations.

Results

Organic mulches enhanced soil water-holding capacity (15.2% increase with jamun leaves) and maintained superior plant water status (relative water content: 85.28% vs 75.00% control). Jamun leaves mulch optimized gas exchange (stomatal conductance: $17.66 \text{ mmol m}^{-2}\text{s}^{-1}$; photosynthetic rate: $8.85 \mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$) while reducing stress indicators (proline: $0.25 \text{ vs } 0.36 \mu\text{mol g}^{-1}$ control). Leaf nutrient concentrations increased significantly under organic treatments (N: 2.27%, P: 0.29%, K: 1.32%). Soil fungal populations increased 30–40% under organic mulches, indicating enhanced biological activity driving nutrient mineralization.

Conclusion

Organic mulches, particularly jamun leaves, create synergistic soil-plant interactions through improved water retention, enhanced microbial-mediated nutrient cycling, and optimized rhizosphere conditions, functioning as integrated soil conditioners that simultaneously address water stress and nutrient limitations in citrus production systems.

Introduction

Soil-plant water relations in semi-arid citrus production systems are constrained by limited water availability, high evapotranspiration rates, and inefficient nutrient cycling, necessitating management strategies that address these interconnected challenges through targeted soil modifications. Mulching represents a fundamental soil management practice that alters the physical, chemical, and biological properties of the rhizosphere, creating cascading effects on plant physiological performance through modified soil-plant interactions.

The mechanistic basis of mulch effects on soil-plant systems involves complex interactions between soil water dynamics, temperature regulation, and microbial-mediated nutrient cycling. Organic mulches contribute to soil organic matter pools, enhancing soil structure, water-holding capacity, and creating favourable conditions for beneficial microbial communities that drive nutrient mineralization processes (Jabran, 2019). These biological transformations fundamentally alter the soil-plant interface by increasing nutrient availability while simultaneously improving soil physical properties that enhance root-soil contact and water uptake efficiency.

Water stress responses in citrus involve physiological adaptations including osmotic adjustment, stomatal regulation, and altered carbon allocation patterns that collectively reduce photosynthetic efficiency and fruit quality. The soil-plant water continuum is particularly sensitive to rhizosphere modifications, where mulching-induced changes in soil moisture retention directly influence plant water status through improved hydraulic conductivity and reduced soil water evaporation (Ow and Mohd Yusof, 2018). Understanding these mechanistic pathways is crucial for optimizing soil management strategies that enhance plant resilience to water stress.

Nutrient dynamics in mulched soils involve complex interactions between organic matter decomposition, microbial activity, and soil chemical properties that regulate nutrient availability and uptake. The decomposition of organic mulches releases nutrients through mineralization processes while simultaneously altering soil pH, cation exchange capacity, and nutrient retention characteristics (Liu et al., 2011). These changes create feedback mechanisms where improved plant nutrition enhances root development and metabolic activity, further optimizing soil-plant nutrient cycling.

Citrus cultivation in semi-arid regions of India faces specific challenges related to soil water management and nutrient availability, particularly in Vertisols soils characterized by high clay content and limited water infiltration rates. The integration of mulching systems in these environments requires an understanding of how different mulch materials interact with soil properties to influence plant physiological responses and overall system productivity.

Previous research has established the beneficial effects of mulching on crop productivity, but critical knowledge gaps persist regarding the mechanistic understanding of soil-plant-microbe interactions under different mulch materials, particularly in the context of semi-arid citrus production systems. While existing studies have documented individual benefits of organic mulching, such as water conservation or nutrient release, the integrative analysis of how mulch composition simultaneously influences soil physical properties, microbial community dynamics, and plant physiological responses through interconnected pathways remains largely unexplored.

Most mulching research focuses on temperate conditions or annual crops, with limited mechanistic investigation of mulch-mediated soil-plant interactions specifically in perennial citrus systems under semi-arid Vertisol conditions. The differential impacts of mulch composition on soil microbial communities and subsequent cascading effects on nutrient cycling represent critical knowledge gaps in soil-plant interaction research. Furthermore, the quantitative comparison of organic versus synthetic mulching systems in terms

of their capacity to create beneficial soil-plant-microbe associations has received insufficient attention in agricultural soil science literature.

This study uniquely addresses these gaps by providing the first comprehensive mechanistic analysis of how different mulching materials influence the soil-plant-microbe continuum in citrus production, specifically focusing on the interconnected effects of mulch-induced changes in soil water retention, microbial community structure, and plant physiological performance. The research advances beyond conventional mulching studies by elucidating the specific pathways through which organic mulch decomposition creates synergistic effects on soil biological activity and plant nutrition, providing quantitative evidence for the superiority of biological enhancement over purely physical soil modifications.

The novelty lies in the integrative approach that connects soil microbial responses to plant physiological outcomes through mulch-mediated modifications of rhizosphere conditions, offering mechanistic insights essential for developing science-based soil management strategies for sustainable citrus production in water-limited environments. This mechanistic framework represents a significant advancement from descriptive mulching studies toward predictive understanding of soil-plant system responses to different management interventions.

Materials and Methods

Site characteristics and experimental design

The experiment was conducted at the College of Horticulture and Forestry, Jhalawar, Rajasthan, India (24°35'N, 76°09'E, 312 m elevation) on mature Nagpur mandarin (*Citrus reticulata* Blanco) trees during 2024–2025. The site is characterized by Vertisols with high clay content (> 40%), bulk density of 1.42 g cm⁻³, and field capacity of 32% (w/w). Climate conditions include mean annual rainfall of 100–120 cm concentrated during monsoon months (July–September), with maximum temperatures reaching 42°C in summer and minimum temperatures of 5°C in winter.

A randomized complete block design with three replications compared nine treatments: T₀ (control - bare soil), T₁ (silver polythene mulch), T₂ (black polythene mulch), T₃ (Weedmat), T₄ (transparent polythene mulch), T₅ (mustard straw), T₆ (coriander straw), T₇ (jamun leaves), and T₈ (soybean straw). Each experimental unit consisted of individual trees with uniform growth characteristics (8–10 years old, similar canopy volume). Mulching materials were applied in a 2 m diameter circle around each tree, maintaining 0.5 m distance from the trunk.

Mulch application and soil preparation

Organic mulches were applied at 8 cm thickness after initial soil characterization, while synthetic mulches were installed as continuous sheets with appropriate anchoring. All organic materials were locally sourced, air-dried to standardize moisture content (< 15%), and chopped to 5–10 cm lengths to ensure uniform

decomposition rates. Initial soil samples were collected from 0–30 cm depth for baseline characterization of physical, chemical, and biological properties.

Soil physical and hydrological measurements

Water-holding capacity determination

Soil water-holding capacity was measured using the gravimetric method following standard protocols. Undisturbed soil samples (100 g) were collected from the 0–20 cm rhizosphere zone using a soil auger at monthly intervals. Samples were air-dried for 48 h, saturated with distilled water for 24 h, and excess gravitational water removed using filter paper drainage for 2 h. Water-holding capacity was calculated as: $WHC (\%) = [(W_1 - W_2)/W_2] \times 100$, where W_1 represents field capacity weight and W_2 represents oven-dry weight (105°C, 24 h). All determinations were performed in triplicate with results expressed as mean $\pm$ standard error.

Soil temperature monitoring

Soil temperatures were recorded at 10 cm depth using digital thermometers positioned within the mulched zone at monthly intervals during midday (12:00–14:00 h). The Temperature Moderation Index (TMI) was calculated to quantify thermal buffering capacity relative to unmulched control treatments.

Plant physiological assessments

Leaf water relations

Relative water content (RWC) was determined monthly using fully expanded leaves from the fourth node of non-fruiting current-year shoots, collected during early morning hours (06:00–08:00 h) to minimize diurnal variation effects. Fresh weight was recorded immediately, followed by turgid weight determination after 24 h of flotation in distilled water under low light conditions. Dry weight was obtained after oven-drying at 70°C for 48 h. RWC was calculated as: $RWC (\%) = [(FW - DW)/(TW - DW)] \times 100$, where FW = fresh weight, TW = turgid weight, and DW = dry weight.

Chlorophyll content analysis

Total chlorophyll content was extracted from leaf samples (0.5 g fresh weight) using 80% acetone following Arnon's method. Absorbance was measured spectrophotometrically at 645 nm and 663 nm wavelengths. Chlorophyll concentration was calculated using standard equations and expressed as mg g⁻¹ fresh weight.

Osmotic stress indicators

Proline content was quantified using the ninhydrin reagent method. Fresh leaf samples (0.5 g) were homogenized in 3% sulfosalicylic acid, and proline concentration was determined spectrophotometrically at

520 nm using L-proline as a standard. Results were expressed as $\mu\text{mol g}^{-1}$ fresh weight.

Gas exchange measurements

Stomatal conductance (g_s) and photosynthetic rate (P_n) were measured using a portable photosynthesis system (CIRAS, USA) under standardized conditions: photosynthetic photon flux density of $1000 \mu\text{mol m}^{-2}\text{s}^{-1}$, chamber temperature of 25°C , and atmospheric CO_2 concentration of 400 ppm. Measurements were conducted on fully expanded, sun-exposed leaves during morning hours (09:00–11:00 h) to ensure optimal physiological activity.

Leaf nutrient analysis

Leaf samples were collected from non-fruiting branches at bimonthly intervals, oven-dried at 70°C for 48 h, and ground to pass through a 0.5 mm sieve. Nitrogen content was determined using the micro-Kjeldahl method following acid digestion. Phosphorus content was analysed using the molybdate blue colorimetric method after wet digestion with $\text{HNO}_3\text{-HClO}_4$. Potassium content was determined using flame photometry following the same digestion procedure. Results were expressed as a percentage of dry matter.

Soil microbial community analysis

Bacterial enumeration

Soil bacterial populations were quantified using the serial dilution plate count method. Fresh soil samples (1 g) from the rhizosphere zone were serially diluted in sterile physiological saline, and appropriate dilutions were plated on nutrient agar medium. Plates were incubated at 28°C for 48 h, and colony-forming units (CFU) were counted and expressed as CFU g^{-1} dry soil.

Fungal enumeration

Soil fungal populations were enumerated using potato dextrose agar medium supplemented with streptomycin (100 mg L^{-1}) to inhibit bacterial growth. Serial dilutions were prepared as described for bacterial analysis, with plates incubated at 25°C for 5–7 days. Fungal colonies were counted and results expressed as CFU g^{-1} dry soil.

Statistical analysis

Data were subjected to analysis of variance (ANOVA) using statistical software, with treatment means separated using Fisher's Least Significant Difference (LSD) test at $P \leq 0.05$. Standard error of means (SEm) and critical difference (CD) values were calculated for each parameter. Correlation analyses were performed to examine relationships between soil properties and plant physiological responses. All statistical analyses assumed normal distribution of residuals and homogeneity of variance, verified through appropriate diagnostic tests.

Results and Discussion

Soil-plant water relations and mulching effects

Water-holding capacity modifications

Mulching treatments significantly altered soil water-holding capacity, with organic materials demonstrating superior performance compared to synthetic alternatives. Jamun leaves mulch (T_7) increased water-holding capacity from 40.9% to 47.1%, representing a 15.2% improvement over initial values. Soybean straw (T_8) and mustard straw (T_5) achieved comparable enhancements of 11.5% and 14.4%, respectively. Synthetic mulches showed moderate improvements (T_2 : 8.0%, T_3 : 5.6%), while the control treatment remained essentially unchanged (+ 1.4%).

These findings reflect fundamental differences in how organic and synthetic materials modify soil physical properties. The decomposition of organic mulches contributes to soil organic matter pools, enhancing soil aggregation and creating stable micropore networks that improve water retention capacity (Lopes et al., 2025). The biochemical composition of jamun leaves, with their favourable carbon-to-nitrogen ratio and polyphenolic content, likely promotes optimal decomposition patterns that enhance soil structure while providing sustained organic matter inputs.

Plant water status responses

Relative water content measurements revealed significant treatment effects throughout the experimental period, with organic mulches maintaining superior plant water status. Jamun leaves mulch consistently supported the highest RWC values: 85.28% (August), 81.95% (October), 72.54% (December), and 72.89% (February), representing improvements of 13.7%, 10.4%, 9.1%, and 8.5% over control treatments, respectively. These sustained improvements demonstrate the capacity of organic mulches to create stable soil-plant water relations through enhanced soil water retention and reduced evaporative losses.

The mechanistic basis for improved plant water status involves multiple pathways. Enhanced soil water-holding capacity directly increases water availability to plant roots, while the physical barrier effect of mulch materials reduces soil surface evaporation by 30–50% compared to bare soil (Ow and Mohd Yusof, 2018). Additionally, organic mulch decomposition improves soil porosity and hydraulic conductivity, facilitating more efficient water uptake by root systems.

Physiological responses to mulch-modified soil conditions

Photosynthetic performance and gas exchange

Gas exchange measurements revealed significant mulching effects on stomatal conductance and photosynthetic rates, with maximum values recorded during October across all treatments. Jamun leaves mulch achieved peak stomatal conductance of $17.66 \text{ mmol m}^{-2}\text{s}^{-1}$ and photosynthetic rate of $8.85 \mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$, representing 15.2% and 7.3% improvements over control treatments, respectively.

These enhanced gas exchange parameters reflect improved soil-plant water relations and optimal rhizosphere conditions created by organic mulching. Higher stomatal conductance facilitates increased CO_2 uptake while maintaining transpirational cooling, indicating that plants under organic mulch treatments experience reduced water stress and can maintain more efficient physiological processes (Berríos et al.,

2024; Kang et al., 2024). The seasonal pattern of maximum activity in post-monsoon conditions corresponds with optimal soil moisture and temperature regimes created by mulch-modified soil environments.

Chlorophyll dynamics and stress indicators

Total chlorophyll content showed marked treatment responses, with jamun leaves mulch achieving maximum values of 0.45 mg g^{-1} in October, representing a 73% increase from initial measurements and 45% improvement over control treatments. This enhanced chlorophyll accumulation indicates improved nitrogen availability through accelerated mineralization processes and reduced drought stress on chloroplast stability.

Proline accumulation patterns provided complementary evidence of stress amelioration under organic mulching systems. Jamun leaves mulch maintained the lowest proline concentrations throughout the study period ($0.25\text{--}0.30 \text{ } \mu\text{mol g}^{-1}$), while control treatments showed elevated levels reaching $0.36 \text{ } \mu\text{mol g}^{-1}$ during peak stress periods. The inverse relationship between mulch effectiveness and proline accumulation demonstrates that organic materials successfully create growing conditions that minimize osmotic stress responses (Hosseini et al., 2022). Figure 1 reflects a comparative evaluation of mulches on the physiological indices of mandarin plants.

Soil-mediated nutrient cycling and plant nutrition

Macronutrient dynamics

Leaf macronutrient analysis revealed significant improvements under organic mulching treatments, with jamun leaves mulch maintaining peak concentrations of nitrogen (2.27%), phosphorus (0.29%), and potassium (1.32%). These enhancements reflect complex interactions between organic matter decomposition, microbial activity, and soil chemical properties that regulate nutrient availability and uptake efficiency.

Nitrogen enhancement under organic mulches results from both direct nutrient contribution through decomposition and improved soil microbial activity that facilitates transformation processes. The sustained elevated nitrogen levels throughout the study period demonstrate the capacity of organic mulches to provide continuous nutrient availability, contrasting with synthetic alternatives that offer only physical benefits without nutrient contribution (Werner and Newton, 2005; Sulok et al., 2015; Sun et al., 2021).

Phosphorus availability increased significantly under organic treatments, particularly with soybean straw (0.30%) and jamun leaves (0.29%). This enhancement reflects accelerated mineralization of organic phosphorus compounds and reduced soil phosphorus fixation through organic acid production during decomposition processes (Othieno, 1973; Xiao-Ri, 2006; Maranguit, 2017). The humic substances generated during organic matter decomposition create chelating environments that maintain phosphorus in plant-available forms while preventing precipitation reactions.

Potassium dynamics under organic mulching involve multiple enhancement mechanisms, including direct release during decomposition, improved soil cation exchange capacity, and enhanced microbial activity that facilitates transformation of fixed potassium forms (Pavinato and Rosolem, 2008; Sanyal et al., 2019). The organic acids released during decomposition compete with potassium for soil adsorption sites, effectively displacing previously bound ions and maintaining exchangeable forms readily available for plant uptake. Figure 2 illustrates seasonal variation in leaf macronutrient concentrations (N, P, K) of Nagpur mandarin under different mulching treatments in Vertisols.

Soil microbial responses and biological activity

Bacterial population dynamics

Soil bacterial populations showed modest but significant responses to mulching treatments. While initial bacterial counts ranged uniformly across treatments ($3.10\text{--}3.35 \times 10^6$ cfu g⁻¹), organic mulches promoted 6–8% increases in final populations, with jamun leaves achieving the highest count (3.55×10^6 cfu g⁻¹). Synthetic mulches and control treatments showed minimal changes, indicating limited biological enhancement under non-organic systems.

Fungal community responses

Soil fungal populations exhibited more pronounced responses to organic mulching treatments, with 30–40% increases observed under organic systems. Jamun leaves recorded the highest fungal density (3.44×10^{-4} cfu g⁻¹), followed by coriander straw (3.28×10^{-4} cfu g⁻¹) and soybean straw (3.25×10^{-4} cfu g⁻¹). This differential response between bacterial and fungal populations suggests that organic mulches particularly favour saprophytic fungi involved in lignocellulosic decomposition processes.

The enhanced microbial activity under organic mulches provides a mechanistic explanation for observed improvements in nutrient cycling and plant performance. Organic mulches function as both substrate and habitat for diverse microbial communities, creating favourable conditions for beneficial soil-plant-microbe associations (Jabran, 2019; Lee *et al*

., 2021). The pronounced fungal response indicates enhanced organic matter turnover and nutrient mineralization capacity, contributing to sustained nutrient availability for plant uptake.

Temperature moderation and soil thermal dynamics

Temperature moderation analysis revealed distinct patterns among mulching treatments, with organic materials demonstrating superior thermal buffering capacity. The Temperature Moderation Index ranged from 96.4 (Weedmat) to 110.4 (jamun leaves), indicating substantial variation in thermal regulation effectiveness. Organic mulches showed elevated TMI values corresponding with "excellent" mineralization favourability ratings, while synthetic mulches achieved moderate thermal stability but limited biological enhancement.

The thermal regulation mechanisms involve both physical and biological processes. Organic materials create insulative layers that dampen extreme temperature fluctuations, as evidenced by 2.39–3.47°C temperature differentials during peak summer months. This thermal buffering capacity is particularly crucial for citrus cultivation, where temperature extremes can significantly impact root zone physiology and nutrient uptake processes.

Implications for sustainable soil management

The consistent superiority of organic mulches, particularly jamun leaves, across physiological and soil parameters demonstrates the multifunctional benefits of organic soil management systems. Unlike synthetic alternatives that provide primarily physical benefits, organic mulches create synergistic effects through simultaneous improvements in soil water retention, nutrient cycling, and biological activity. These findings have significant implications for sustainable citrus production in semi-arid environments, where integration of locally available organic materials provides dual benefits of waste utilization and soil health enhancement, contributing to circular agricultural systems that reduce dependence on external inputs while improving system resilience. The mechanistic understanding developed demonstrates that effective soil management requires recognition of the interconnected nature of physical, chemical, and biological soil processes, with organic mulching systems optimizing these interactions by creating favorable conditions for beneficial soil-plant-microbe associations that enhance overall system productivity and sustainability.

Conclusions

This investigation demonstrates that organic mulching systems fundamentally alter soil-plant interactions through interconnected modifications of physical, chemical, and biological soil properties that collectively enhance citrus physiological performance under semi-arid conditions. Jamun leaves mulch optimized soil-plant water relations by increasing soil water-holding capacity (15.2% improvement) while enhancing microbial-mediated nutrient cycling, resulting in superior plant water status (RWC: 85.28%) and photosynthetic performance (P_n : $8.85 \mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$). While synthetic mulches provide physical soil protection, organic materials create dynamic soil environments through continuous organic matter inputs that support enhanced microbial activity (30–40% increase in fungal populations) and sustained nutrient availability (N: 2.27%, P: 0.29%, K: 1.32%). This biological enhancement represents a fundamental distinction between management approaches that modify soil physical properties versus those that optimize soil-plant-microbe associations. The pronounced fungal proliferation under organic mulches indicates enhanced decomposition capacity and organic matter turnover, creating favorable conditions for nutrient mineralization and temperature moderation that enhance plant resilience to environmental stresses. From a soil management perspective, organic mulching systems function as integrated soil conditioners that address multiple limiting factors simultaneously, with locally available materials like jamun leaves providing sustainable pathways for soil health improvement while contributing to circular agricultural systems and resilient production under changing environmental conditions.

Declarations

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Competing Interests

The authors declare that they have no competing interests.

Author's Contribution

Rinku Saini conceptualized the research, conducted field implementation, and performed data collection and analysis. **Prerak Bhatnagar** provided technical guidance and supervision throughout the research implementation. **Jitendra Singh** contributed to the scientific interpretation and outcomes of the research work. **Hemraj Chhipa** assisted with laboratory analysis. **Anchal Sharma** contributed to manuscript formatting and preparation.

Data Availability

All data generated or analysed during this study are included in this published article.

Consent to Publish declaration: Not applicable

Consent to Participate declaration: Not applicable

Ethics declaration: Not applicable

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Tables

Table 1. Impact of mulches on the water-holding capacity (%) of Nagpur mandarin

S.No.	Treatments	Initial WHC (%)	Final WHC (%)
1.	T ₀ (Control)	42.50	43.10
2.	T ₁ (Silver polythene)	40.70	42.80
3.	T ₂ (Black polythene)	40.20	43.40
4.	T ₃ (Weedmat)	41.30	43.60
5.	T ₄ (Transparent polythene)	38.70	41.70
6.	T ₅ (Mustard straw)	38.80	44.40
7.	T ₆ (Coriander straw)	41.60	45.60
8.	T ₇ (Jamun leaves)	40.90	47.10
9.	T ₈ (Soybean straw)	41.80	46.60
	SEm (±)	0.56	0.88
	CD 5%	1.67	2.64

Table 2 Impact of mulches on variance in Relative Water Content (%) in leaves of Nagpur mandarin

S.No.	Treatments	Initial RWC (%)	August 2024	October 2024	December 2024	February 2025
1.	T ₀ (Control)	68.45	75.00	74.25	66.48	67.20
2.	T ₁ (Silver polythene)	66.52	78.09	77.26	67.75	68.42
3.	T ₂ (Black polythene)	67.25	78.89	77.25	69.80	70.00
4.	T ₃ (Weedmat)	66.25	80.00	79.68	69.58	69.89
5.	T ₄ (Transparent polythene)	64.80	79.94	78.65	68.15	69.73
6.	T ₅ (Mustard straw)	66.58	80.75	79.64	69.45	70.08
7.	T ₆ (Coriander straw)	67.25	83.37	80.75	70.84	70.15
8.	T ₇ (Jamun leaves)	65.72	85.28	81.95	72.54	72.89
9.	T ₈ (Soybean straw)	66.75	82.53	80.84	70.25	70.44
	SEm (±)	0.85	1.25	0.84	0.89	0.93
	CD 5%	NS	3.74	2.51	2.68	2.80

Table: 3 Impact of mulches on variance in Total Chlorophyll (mg g⁻¹) in leaves of Nagpur mandarin

S.No.	Treatments	Initial Total Chlorophyll (mg g ⁻¹)	August 2024	October 2024	December 2024	February 2025
1.	T ₀ (Control)	0.29	0.29	0.31	0.29	0.27
2.	T ₁ (Silver polythene)	0.29	0.30	0.31	0.30	0.28
3.	T ₂ (Black polythene)	0.30	0.32	0.34	0.32	0.29
4.	T ₃ (Weedmat)	0.31	0.32	0.34	0.31	0.30
5.	T ₄ (Transparent polythene)	0.28	0.29	0.32	0.30	0.28
6.	T ₅ (Mustard straw)	0.28	0.31	0.40	0.38	0.34
7.	T ₆ (Coriander straw)	0.29	0.32	0.42	0.40	0.35
8.	T ₇ (Jamun leaves)	0.26	0.34	0.45	0.43	0.38
9.	T ₈ (Soybean straw)	0.28	0.31	0.43	0.41	0.35
	SEm (±)	0.01	0.01	0.01	0.01	0.02
	CD 5%	NS	0.03	0.04	0.04	0.06

Table: 4 Impact of mulches on Proline content (μmol g⁻¹)in leaves of Nagpur mandarin

S.No.	Treatments	Initial Proline 2024	August 2024	October 2024	December 2024	February 2025
1.	T ₀ (Control)	0.41	0.30	0.32	0.36	0.29
2.	T ₁ (Silver polythene)	0.39	0.29	0.30	0.35	0.28
3.	T ₂ (Black polythene)	0.43	0.28	0.29	0.35	0.28
4.	T ₃ (Weedmat)	0.48	0.29	0.31	0.34	0.27
5.	T ₄ (Transparent polythene)	0.49	0.28	0.32	0.34	0.28
6.	T ₅ (Mustard straw)	0.43	0.27	0.30	0.32	0.27
7.	T ₆ (Coriander straw)	0.42	0.26	0.29	0.32	0.27
8.	T ₇ (Jamun leaves)	0.40	0.25	0.28	0.30	0.25
9.	T ₈ (Soybean straw)	0.47	0.28	0.31	0.31	0.26
	SEm (±)	0.01	0.01	0.01	0.01	0.01
	CD 5%	0.02	0.03	0.02	0.02	0.02

Table 5: Impact of mulches on Leaf nitrogen content (%) in leaves of Nagpur mandarin

S.No.	Treatments	Initial Leaf N (%)	August 2024	October 2024	December 2024	February 2025
1.	T ₀ (Control)	2.10	2.10	2.09	2.08	2.06
2.	T ₁ (Silver polythene)	2.05	2.12	2.10	2.08	2.07
3.	T ₂ (Black polythene)	2.18	2.20	2.18	2.16	2.16
4.	T ₃ (Weedmat)	2.16	2.18	2.16	2.16	2.15
5.	T ₄ (Transparent polythene)	2.20	2.19	2.18	2.16	2.15
6.	T ₅ (Mustard straw)	2.15	2.25	2.23	2.22	2.20
7.	T ₆ (Coriander straw)	2.12	2.26	2.25	2.23	2.21
8.	T ₇ (Jamun leaves)	2.15	2.27	2.26	2.25	2.23
9.	T ₈ (Soybean straw)	2.17	2.24	2.24	2.22	2.20
	SEm (±)	0.03	0.04	0.03	0.03	0.02
	CD 5%	NS	0.11	0.09	0.08	0.06

Table 6: Impact of mulches on Leaf phosphorus content (%) in leaves of Nagpur mandarin

Treatments	Initial Leaf P (%)	August 2024	October 2024	December 2024	February 2025
T ₀ (Control)	0.21	0.22	0.21	0.20	0.19
T ₁ (Silver polythene)	0.20	0.23	0.22	0.21	0.20
T ₂ (Black polythene)	0.24	0.26	0.24	0.22	0.21
T ₃ (Weedmat)	0.22	0.25	0.24	0.22	0.22
T ₄ (Transparent polythene)	0.23	0.24	0.24	0.23	0.21
T ₅ (Mustard straw)	0.23	0.27	0.26	0.25	0.24
T ₆ (Coriander straw)	0.21	0.25	0.24	0.23	0.23
T ₇ (Jamun leaves)	0.21	0.29	0.28	0.28	0.25
T ₈ (Soybean straw)	0.20	0.30	0.28	0.27	0.25
SEm (±)	0.01	0.02	0.01	0.01	0.01
CD 5%	NS	0.05	0.04	0.04	0.03

Table 7: Impact of mulches on Leaf potassium content (%) in leaves of Nagpur mandarin

Treatments	Initial Leaf K (%)	August 2024	October 2024	December 2024	February 2025
T ₀ (Control)	1.20	1.23	1.21	1.19	1.18
T ₁ (Silver polythene)	1.22	1.24	1.23	1.21	1.20
T ₂ (Black polythene)	1.23	1.25	1.25	1.23	1.22
T ₃ (Weedmat)	1.21	1.25	1.24	1.23	1.21
T ₄ (Transparent polythene)	1.22	1.25	1.23	1.22	1.21
T ₅ (Mustard straw)	1.20	1.28	1.26	1.25	1.23
T ₆ (Coriander straw)	1.21	1.30	1.28	1.25	1.24
T ₇ (Jamun leaves)	1.20	1.32	1.29	1.27	1.25
T ₈ (Soybean straw)	1.22	1.29	1.27	1.26	1.23
SEm (±)	0.02	0.02	0.01	0.01	0.01
CD 5%	NS	0.05	0.04	0.03	0.03

Table 8: Impact of mulches on Stomatal conductance (gs) in leaves of Nagpur mandarin

Treatments	Initial gs (mmol ⁻² s ⁻¹)	August 2024	October 2024	December 2024	February 2025
T ₀ (Control)	8.00	12.60	15.33	10.34	12.25
T ₁ (Silver polythene)	9.50	13.36	16.24	10.45	12.46
T ₂ (Black polythene)	9.15	15.64	16.54	10.68	12.65
T ₃ (Weedmat)	7.65	12.00	15.00	10.58	12.59
T ₄ (Transparent polythene)	8.80	13.10	14.32	10.40	12.48
T ₅ (Mustard straw)	7.92	13.65	16.34	10.69	12.70
T ₆ (Coriander straw)	6.98	15.35	16.00	10.52	12.80
T ₇ (Jamun leaves)	7.65	15.33	17.66	11.35	12.92
T ₈ (Soybean straw)	8.45	13.56	15.38	10.64	12.72
SEm (±)	0.11	0.18	0.23	0.15	0.11
CD 5%	0.32	0.55	0.68	0.45	0.34

Table 9: Impact of mulches on Photosynthetic rate in leaves of Nagpur mandarin

Treatments	Initial Pn ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)	August 2024	October 2024	December 2024	February 2025
T ₀ (Control)	4.56	7.20	8.25	6.10	6.98
T ₁ (Silver polythene)	4.86	7.54	8.40	6.24	7.05
T ₂ (Black polythene)	4.95	7.98	8.50	6.32	7.15
T ₃ (Weedmat)	4.46	7.05	7.98	6.29	7.12
T ₄ (Transparent polythene)	4.97	7.24	7.71	6.21	7.06
T ₅ (Mustard straw)	4.88	7.41	8.48	6.58	7.22
T ₆ (Coriander straw)	4.71	7.91	8.09	6.79	7.29
T ₇ (Jamun leaves)	4.86	8.16	8.85	7.10	7.35
T ₈ (Soybean straw)	5.00	7.74	8.28	6.74	7.24
SEm ($\pm$)	0.06	0.13	0.10	0.11	0.07
CD 5%	0.17	0.38	0.30	0.34	0.21

Table 10: Impact of mulches on Soil temperature ($^{\circ}\text{C}$) in the canopy soil of Nagpur mandarin

Treatments	Initial Value June	July24	Aug.24	Sep.24	Oct. 24	Nov.24	Dec.24	Jan. 25	Feb.25
T ₀ (Control)	39.50	31.54	27.00	26.05	23.02	20.15	17.02	15.25	17.30
T ₁ (Silver polythene)	39.15	31.84	27.95	25.25	22.85	20.05	17.14	15.24	17.22
T ₂ (Black polythene)	38.84	31.05	27.85	26.05	22.48	20.00	17.10	15.02	16.95
T ₃ (Weedmat)	39.25	32.62	28.72	26.84	23.54	20.72	17.34	15.46	17.74
T ₄ (Transparent polythene	39.64	32.05	28.02	26.48	23.25	20.24	17.25	15.00	16.98
T ₅ (Mustard straw)	38.52	29.45	26.24	24.58	20.48	18.28	15.23	14.65	15.83
T ₆ (Coriander straw)	38.85	29.64	26.72	24.15	20.24	18.00	15.15	14.88	15.00
T ₇ (Jamun leaves)	39.02	28.24	25.35	25.05	21.08	19.07	16.48	14.05	15.23
T ₈ (Soybean straw)	38.46	28.15	25.05	25.02	21.32	19.31	16.23	14.00	15.15
Mean	39.02	30.50	26.98	25.49	22.02	19.53	16.54	14.83	16.37

Table 11: Soil temperature moderation index (TMI)

Treatments	TMI	Temperature Stability	Mineralization Favourability
T0 (Control)	100.6	Poor	Moderate
T1 (Silver polythene)	99.3	Poor	Moderate
T2 (Black polythene)	99.5	Poor	Moderate
T3 (Weedmat)	96.4	Moderate	Good
T4 (Transparent polythene)	101.3	Poor	Moderate
T5 (Mustard straw)	105.7	Poor	Excellent*
T6 (Coriander straw)	105.9	Poor	Excellent*
T7 (Jamun leaves)	110.4	Poor	Excellent*
T8 (Soybean straw)	108.7	Poor	Excellent*

Table 12: Impact of mulches on Soil bacteria in Nagpur mandarin

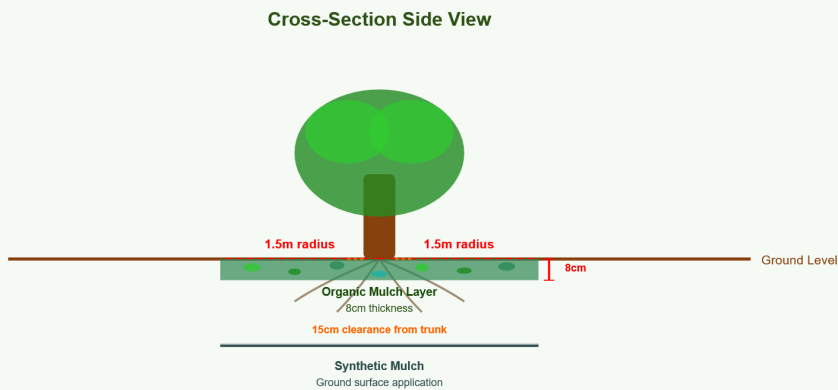
Treatments	Initial Soil bacteria (10^6 cfug $^{-1}$)	Final Soil bacteria (10^6 cfug $^{-1}$)
T ₀ (Control)	3.25	3.27
T ₁ (Silver polythene)	3.34	3.36
T ₂ (Black polythene)	3.10	3.12
T ₃ (Weedmat)	3.35	3.37
T ₄ (Transparent polythene)	3.35	3.36
T ₅ (Mustard straw)	3.30	3.49
T ₆ (Coriander straw)	3.28	3.50
T ₇ (Jamun leaves)	3.29	3.55
T ₈ (Soybean straw)	3.30	3.47
SEm ($\pm$)	0.05	0.04
CD 5%	NS	0.13

Table: 4.13 Impact of mulches on Soil fungi in Nagpur mandarin

S.No.	Treatments	Initial Soil fungi ($\times 10^{-4}$ cfug $^{-1}$)	Final Soil fungi ($\times 10^{-4}$ cfug $^{-1}$)
1.	T ₀ (Control)	2.42	2.44
2.	T ₁ (Silver polythene)	2.41	2.42
3.	T ₂ (Black polythene)	2.42	2.44
4.	T ₃ (Weedmat)	2.47	2.49
5.	T ₄ (Transparent polythene)	2.39	2.43
6.	T ₅ (Mustard straw)	2.45	3.20
7.	T ₆ (Coriander straw)	2.48	3.28
8.	T ₇ (Jamun leaves)	2.44	3.44
9.	T ₈ (Soybean straw)	2.46	3.25
	SEm ($\pm$)	0.03	0.04
	CD 5%	NS	0.12

Figures

Mulching Application Schematic: 4-Year-Old Nagpur Mandarin Plants
1.5m Radius Application | 8cm Organic Mulch Thickness | Ground Surface Synthetic Mulches



Application Guidelines

Tree Specifications:

- Age: 4 years
- Variety: Nagpur mandarin
- Soil: Heavy clay

Application Area:

- Radius: 1.5 meters from trunk
- Clearance: 15cm from trunk
- Total area: 7.07 m²

Organic Mulches:

- Thickness: 8cm uniform layer
- Material: Loose application
- Replenishment: As needed

Synthetic Mulches:

- Application: Ground surface
- Fixing: Secure edges
- Drainage: Perforate if needed

Recommended: T7 (Jamun Leaves)

Best overall performance for sustainable mandarin cultivation

15cm trunk clearance

Treatment Specifications and Performance Results

Treatment	Mulch Type	Application	WHC (%)	RWC Peak (%)	Chlorophyll (mg/g)	Proline (μmol/g)	Stomatal Conductance	Performance	Rank
T0	Control (No mulch)	-	40.9	75.00	0.26	0.36	15.33	Poorest	9
T1	White Polythene	Ground surface	43.2	78.50	0.32	0.32	16.10	Moderate	7
T2	Black Polythene	Ground surface	44.1	79.20	0.35	0.31	16.45	Good	6
T3	Weedmat	Ground surface	44.5	80.00	0.33	0.30	16.80	Good	5
T4	Transparent Polythene	Ground surface	43.8	79.94	0.34	0.31	16.20	Good	8
T5	Mustard Straw	8cm thick layer	46.5	82.15	0.39	0.28	17.20	Very Good	4
T6	Coriander Straw	8cm thick layer	44.9	83.50	0.42	0.27	17.50	Very Good	3
T7	Jamun Leaves	8cm thick layer	47.1	85.28	0.45	0.25	17.66	EXCELLENT	1
T8	Soybean Straw	8cm thick layer	45.7	83.80	0.41	0.26	17.40	Very Good	2

Figure 1

Comparative performance of organic-inorganic mulches on the physiological indices of mandarin plants

Effect of Mulches on Macronutrient Status in Nagpur Mandarin Plants

February 2025)

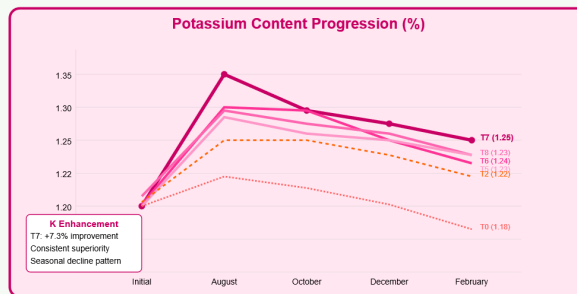
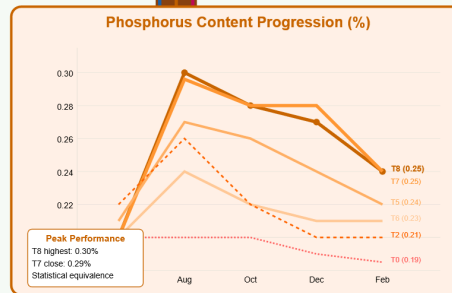
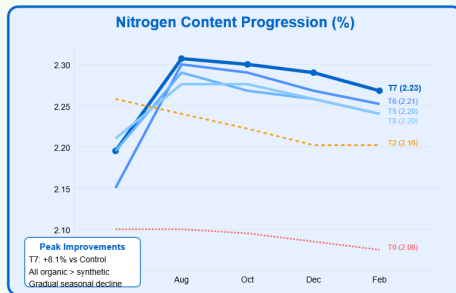
Complete Treatment Performance Comparison

Treatment	Mulch Type	N Peak (%)	P Peak (%)	K Peak (%)	N Final (%)	P Final (%)	K Final (%)	Overall Rank	Performance
T7	Jamun Leaves	2.27	0.29	1.32	2.23	0.25	1.25	1	EXCELLENT
T8	Soybean Straw	2.24	0.30	1.29	2.20	0.25	1.23	2	Very Good
T6	Coriander Straw	2.26	0.25	1.30	2.21	0.23	1.24	3	Very Good
T5	Mustard Straw	2.25	0.27	1.28	2.20	0.24	1.23	4	Good
T3	Weedmat	2.18	0.25	1.25	2.15	0.22	1.21	5	Moderate
T2	Black Polythene	2.20	0.26	1.25	2.16	0.21	1.22	6	Moderate
T4	Transparent Polythene	2.19	0.24	1.25	2.15	0.21	1.21	7	Fair
T1	Silver Polythene	2.12	0.23	1.24	2.07	0.20	1.20	8	Below Average
T0	Control (No mulch)	2.10	0.22	1.23	2.06	0.19	1.18	9	POOREST

Statistical Analysis:

• SEM (±): N = 0.02-0.04, P = 0.01-0.02, K = not specified
 • CD 5%: Significant differences established for all nutrients across seasons

• Clear superiority of organic mulches over synthetic and control treatments
 • T7 (Jamun leaves) consistently ranks highest for N and K, T8 best for P



Nutrient Uptake Enhancement Summary

Top Performing Treatments

- N** T7 (Jamun Leaves): 2.27% peak, +8.1% vs control
- P** T8 (Soybean Straw): 0.30% peak, T7 close at 0.29%
- K** T7 (Jamun Leaves): 1.32% peak, +7.3% vs control

Seasonal Trend Analysis

Peak Season: August 2024

- All nutrients reached maximum levels
- Post-monsoon optimal uptake conditions
- Organic mulches showed superior performance

Decline Pattern: August → February

- Gradual nutrient decline in all treatments

Mulch Type Performance Ranking

- 1. Organic Mulches**: Superior across all nutrients
- 2. Synthetic Mulches**: Moderate improvements
- 3. Control**: Poorest performance

Statistical Significance:

- CD 5% achieved for all nutrients in all months
- Clear differentiation between treatments

Nutrient Uptake Enhancement Mechanisms

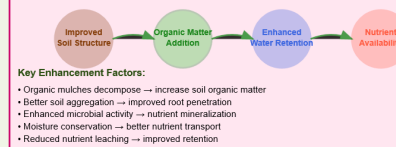


Figure 2

Impact of mulches on the leaf nutrient uptake and seasonal utilization of N, P, and K in Mandarin plants under Vertisols