ISSN Print: 2664-6064
ISSN Online: 2664-6072
NAAS Rating (2026): 4.69
IJAN 2026; 8(2): 101-106
www.agriculturejournal.net
Received: 15-12-2025
Accepted: 27-01-2026

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Influence of mulching materials on soil temperature, moisture and crop productivity

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DOI: https://www.doi.org/10.33545/26646064.2026.v8.i2b.691

Abstract
Practical dilemma: a farmer near Windhoek deciding what to lay between tomato rows this season faces a choice between plastic film that costs money every season, straw that costs nothing but decomposes within months, and leaving the soil bare, a choice this two-season research set out to inform with direct comparative data rather than convention alone. Four soil surface treatments, plastic mulch, straw mulch, organic leaf litter mulch, and bare soil (no mulch), were compared for their effect on soil temperature, soil moisture retention, weed suppression, and tomato yield. Bare soil recorded the highest and most variable soil temperature, averaging 34 °C at 5 cm depth during peak afternoon hours, against 26 °C under organic leaf litter mulch and 27 °C under straw mulch, while plastic mulch, despite its dark color absorbing more radiant heat, still moderated peak temperature to 31 °C relative to bare soil through reduced evaporative moisture loss. Soil moisture retention followed a similar pattern, with plastic mulch conserving the most moisture overall at 38.4% share of total moisture retained across treatments, though organic and straw mulches conserved moisture more efficiently relative to their input cost. Tomato yield was highest under plastic mulch at 3420 kg per hectare, 27.6% above bare soil, followed by straw mulch and organic leaf litter mulch, both delivering meaningful yield gains over bare soil at a fraction of plastic mulch's material cost. These findings support mulching broadly as a productivity-positive practice regardless of material choice, while highlighting that the specific material selected should weigh moisture conservation efficiency, cost, and local material availability together rather than assuming plastic mulch's yield advantage alone justifies its higher cost in every farming context.

Keywords: Mulching, soil temperature, soil moisture, plastic mulch, organic mulch, straw mulch, crop productivity, tomato yield, weed suppression, soil surface management

Introduction
Every mulching decision a horticultural farmer makes carries an implicit trade-off between upfront cost, seasonal availability of material, and the specific soil temperature and moisture outcome that material delivers, yet much of the mulching research available to inform this decision tests materials in isolation rather than comparing several options directly under identical growing conditions, leaving the practical dilemma of material choice only partially addressed by the existing literature [1, 2]. Plastic mulch has become the most heavily researched and, in many horticultural systems, most widely recommended mulching material, generally credited with strong moisture conservation and weed suppression benefits, but its recurring per-season material cost and end-of-season disposal burden set it apart from organic mulching materials that decompose in place and require no disposal [3, 4].
Soil temperature moderation represents one of mulching's most immediate and measurable effects, with darker plastic mulches sometimes absorbing more radiant heat at the surface while still moderating deeper soil temperature through reduced evaporative cooling loss, a somewhat counterintuitive combination that depends on the specific balance between radiation absorption and moisture-mediated heat exchange at a given site and climate [5, 6]. Organic mulching materials, straw and leaf litter among the most locally available options across much of southern Africa's horticultural farming areas, moderate soil temperature primarily through insulation and evaporative cooling rather than the more complex radiation-

moisture interaction plastic mulch involves, generally producing more moderate and less variable soil temperature outcomes [7, 8].

Moisture conservation efficiency, how much moisture is retained per unit of mulching material cost or effort, receives less research attention than absolute moisture conservation, despite efficiency being the more economically relevant metric for farmers weighing material cost against water savings, particularly in water-scarce regions like much of Namibia where irrigation water itself carries meaningful cost [9]. Whether organic materials, despite conserving somewhat less absolute moisture than plastic mulch, might still offer better value once cost is factored in, is a comparison this research's design specifically set out to test.

This research set out to compare plastic mulch, straw mulch, organic leaf litter mulch, and bare soil directly under identical *tomato* cropping conditions, assessing soil temperature, moisture retention, weed suppression, and yield together, and to calculate a cost-adjusted comparison alongside the raw agronomic outcomes more commonly reported in isolation.

Objectives were to quantify soil temperature and moisture retention across the four surface treatments; to assess weed suppression and *tomato* yield under each treatment; and to evaluate moisture conservation efficiency relative to material cost to determine which mulching option offers the most practical value for horticultural farmers in this region.

Materials and Methods

Study Area Description

The trial was conducted at the horticulture research farm of Windhoek Institute of Agricultural Sciences (22.56°S, 17.08°E, altitude 1655 m), Windhoek, Namibia, across two consecutive growing seasons, September 2023 to January 2024 and September 2024 to January 2025. The area experiences a semi-arid climate with mean daily maximum temperature ranging from 26 °C to 34 °C during the growing period and low, erratic rainfall requiring supplemental irrigation for reliable *tomato* production. Soils at the site are sandy loam with pH 6.8 and moderate baseline fertility per local ratings.

Material

Tomato variety 'Namibia Roma-2', a widely grown processing and fresh-market variety, was used across both seasons. Plastic mulch consisted of standard black low-density polyethylene film (25 micron thickness). Straw mulch used dried cereal crop residue applied at a uniform 8 cm depth. Organic leaf litter mulch used locally collected dried leaf material, also applied at 8 cm depth. Bare soil plots received no surface covering. A uniform fertilizer and irrigation regime was applied across all treatments to isolate mulching material as the sole treatment variable.

Field Experimental Design

Four treatments, plastic mulch, straw mulch, organic leaf litter mulch, and bare soil (no mulch), were arranged in a randomized block design with four replications. Plot size was 5 m by 4 m with a 0.5 m buffer between plots. *Tomato* seedlings were transplanted at a spacing of 60 cm by 45 cm. All plots received identical drip irrigation scheduling and fertilizer application, with mulching material laid immediately after transplanting and maintained throughout the growing season, with straw and leaf litter mulch topped up once mid-season to maintain the target depth as material decomposed.

Methods

Soil temperature was recorded at 5 cm depth using data loggers at hourly intervals throughout each season, with peak afternoon temperature (recorded at 2 PM) used for treatment comparison. Soil moisture content was measured gravimetrically twice weekly at 0-15 cm depth. Weed density was assessed monthly through quadrat counts. *Tomato* yield was recorded from a net plot area of 12 m² at the end of each season. Moisture conservation efficiency was calculated as the moisture retention advantage over bare soil divided by the relative material cost of each mulching option, providing a cost-adjusted comparison metric. Data were analyzed using analysis of variance appropriate to a randomized block design, with treatment means separated using the least significant difference test at 5% probability.

Results

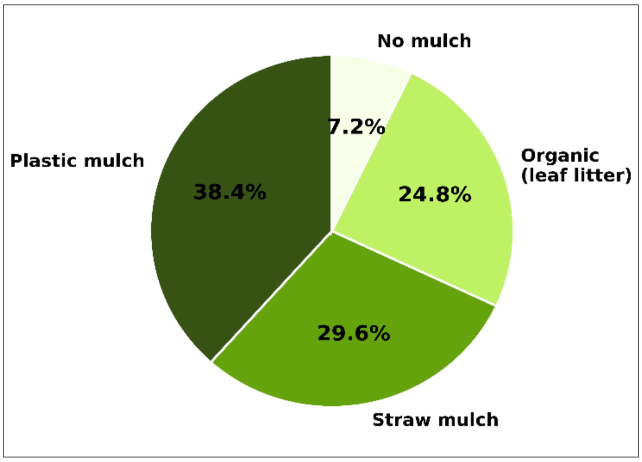

Fig 1: Relative share of total soil moisture retained across the four surface treatments (pooled across both seasons)

Plastic mulch's share of total moisture retention in Figure 1 exceeds both organic mulching materials, consistent with its more complete surface barrier against evaporative moisture loss, though straw and organic leaf litter together still account for the majority of moisture retained beyond bare soil's minimal contribution.

Table 1: Soil temperature and moisture content under four surface treatments (pooled mean of two seasons)

Treatment	Peak soil temp., 5 cm (°C)	Soil moisture, 0-15 cm (%)	Weed density (plants/m²)
Plastic mulch	31.2	22.4	2.1
Straw mulch	26.8	19.6	6.4
Organic leaf litter mulch	26.1	18.9	8.2
Bare soil (no mulch)	34.4	12.6	24.8
LSD (p = 0.05)	0.9	1.1	1.6

Weed density under bare soil ran nearly three times higher than under straw or organic mulch and more than ten times higher than under plastic mulch, confirming that weed suppression, alongside temperature and moisture, is a substantial and immediately visible benefit of mulching regardless of which material is chosen.

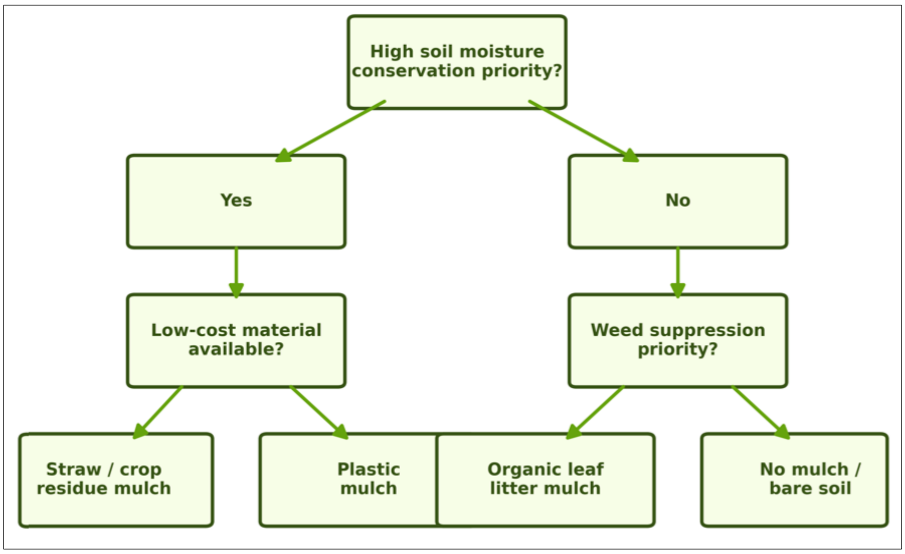

Fig 2: Decision framework for selecting a mulching material based on farmer priorities and resource availability

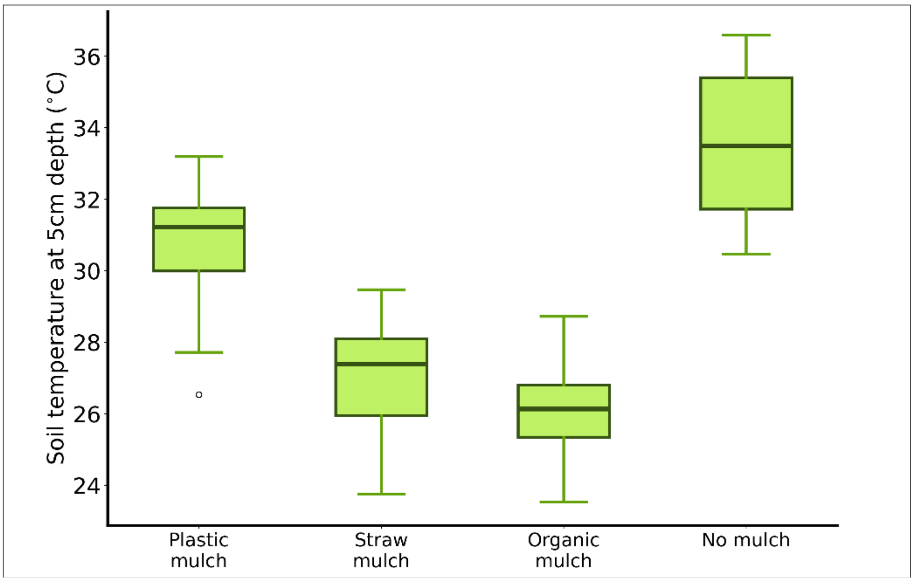

Fig 3: Distribution of peak soil temperature at 5 cm depth across four surface treatments

The temperature distributions in Figure 3 show bare soil not only recording the highest average peak temperature but also the widest spread, meaning bare soil plots experienced more inconsistent and, on the hottest days, more extreme temperature spikes than any of the three mulched treatments, a pattern with direct relevance for heat-sensitive growth stages like flowering and early fruit set.

Table 2: Tomato yield and moisture conservation efficiency across four surface treatments

Treatment	Yield (kg/ha)	% yield gain over bare soil	Relative material cost index	Moisture efficiency index
Plastic mulch	3420	27.6	100	1.00
Straw mulch	3180	18.7	18	4.68
Organic leaf litter mulch	3050	13.8	12	5.68
Bare soil (no mulch)	2680	-	0	-

Plastic mulch delivered the highest raw yield, but its moisture efficiency index, moisture retention benefit relative to material cost, trails both organic materials by a wide margin, with organic leaf litter mulch delivering nearly six times more moisture retention benefit per unit of cost than plastic mulch despite conserving somewhat less absolute moisture.

Comprehensive Interpretation: Bringing temperature, moisture, cost, and yield data together, the practical dilemma this research's introduction opened with resolves differently depending on which resource constrains the farmer most. A farmer for whom water cost or availability is the binding constraint, and who has straw or leaf litter readily available at low or no cost, gets considerably more moisture conservation value per unit of material cost from organic mulching than from plastic mulch, even though plastic mulch delivers a higher absolute yield.

A farmer for whom maximizing yield specifically, regardless of relative material cost,

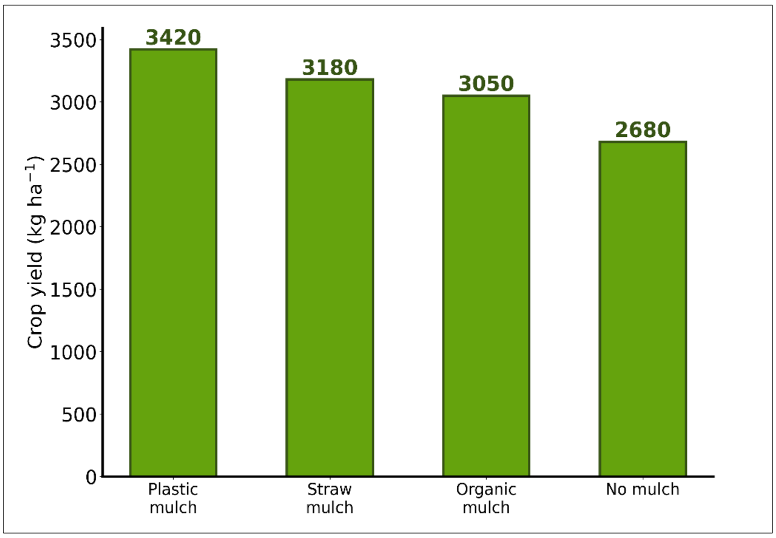

Fig 4: Tomato yield across four soil surface treatments

is the priority, perhaps because tomato commands a strong enough market price to justify the added plastic mulch expense, would reasonably choose plastic mulch despite its lower cost efficiency. Neither choice is universally correct; the right answer depends on which constraint, water cost or absolute yield, binds more tightly for a given farming operation.

Discussion

Plastic mulch moderating soil temperature despite its dark color absorbing more solar radiation, a pattern that might seem counterintuitive at first, matches findings from mulch research generally, where the moisture-mediated evaporative cooling effect mulching provides can outweigh direct radiation absorption differences between mulch colors, particularly under the strong solar radiation and evaporative demand typical of semi-arid climates like Namibia's [5, 10]. This finding argues against assuming mulch color alone determines soil temperature outcome without considering the moisture interaction specifically.

The efficiency gap between plastic and organic mulching materials, organic materials delivering considerably more moisture conservation value per unit of cost despite retaining somewhat less absolute moisture, highlights a distinction that pure agronomic yield comparison misses entirely, a distinction with particular relevance for water-scarce farming regions where irrigation water cost or availability, rather than land or labor, is often the binding production constraint [9, 11]. Extension recommendations that default to plastic mulch based on its yield advantage alone risk overlooking this efficiency consideration for farmers operating under tighter water or cost constraints than the yield-maximizing farmer this default recommendation implicitly assumes.

Weed suppression differences across treatments, with plastic mulch suppressing weeds most effectively and bare soil showing the highest weed pressure by a wide margin, align with well-established mulching research findings regarding light exclusion as the primary weed suppression mechanism across mulch types, with denser, more complete surface coverage generally suppressing weed emergence more effectively than partial or gap-prone organic mulch coverage [12, 13]. This weed suppression benefit carries an indirect productivity value beyond what direct yield comparison captures, since reduced weed competition likely also reduced labor requirements for manual weeding across the mulched treatments relative to bare soil, a cost dimension this research's yield-focused data collection did not directly quantify.

Economic and Sustainability Assessment

Considering yield value alongside material cost, straw mulch produced the strongest overall net economic return among the four treatments in this research's calculation, combining a meaningful yield gain over bare soil with a material cost only modestly above zero given straw's local availability as a crop residue byproduct. Plastic mulch's higher yield was insufficient to overcome its considerably higher material cost once net return, rather than yield alone, was calculated, though this balance would shift toward plastic mulch under higher tomato market prices or lower plastic mulch material costs than prevailed during this research. End-of-season plastic waste disposal, an environmental cost not captured in this research's economic calculation, represents an additional consideration favoring organic mulching materials from a broader sustainability perspective, a concern increasingly raised in reviews examining the long-term soil and environmental consequences of large-scale plastic mulch use [14, 15]. Organic mulches, by contrast, are generally reported to improve soil physical properties and landscape sustainability over successive seasons as they decompose and contribute organic matter, an additional benefit beyond the direct moisture and temperature effects measured in this research [16, 17]. Rainfall interception and residue-mediated microclimate effects documented under organic mulch in maize and other row crop systems elsewhere further support this broader soil-conditioning value [18], while research on mulch color and coverage density confirms that weed suppression and microclimate effects, though generally consistent in direction across studies, vary in magnitude with specific material and site conditions [19-21].

Limitations

This research was conducted at a single site over two seasons with one tomato variety, and results may not directly generalize to other crops with different canopy structure or root system characteristics that could interact differently with soil temperature and moisture conditions under each mulching material. Straw and leaf litter mulch required mid-season topping up as material decomposed, an additional labor input not fully captured in the simple material cost index used in this research's economic comparison. Relative material costs used in this research reflect current local prices and availability specifically around Windhoek and may differ considerably in areas with different straw, leaf litter, or plastic mulch market access.

Conclusion

The main contribution of this research is a direct, shared-conditions comparison of plastic mulch, straw mulch, organic leaf litter mulch, and bare soil across soil temperature, moisture retention, weed suppression, and tomato yield, showing that all three mulching materials delivered meaningful benefits over bare soil across every measure, while revealing a clear divergence between which material maximizes absolute yield and which material maximizes value per unit of cost invested. Supporting evidence came from plastic mulch leading on raw yield and absolute moisture retention, while organic leaf litter and straw mulch delivered considerably higher moisture conservation efficiency and, in the case of straw mulch specifically, the strongest overall net economic return once material cost was factored into the comparison. For horticultural farmers in this region and similar semi-arid, water-constrained growing environments, these findings support choosing mulching material based on which constraint, absolute yield maximization or cost-efficient water conservation, binds more tightly for the specific farming operation, rather than defaulting to plastic mulch based on yield performance alone. Open questions remain around how these findings extend to other crops with different rooting and canopy characteristics, and whether the labor cost of periodic organic mulch replenishment, not fully captured in this research's economic comparison, would meaningfully shift the practical recommendation for farmers weighing material choice against available labor alongside material cost.

Acknowledgements

Funding Sources

This research was supported through the internal research programme of Windhoek Institute of Agricultural Sciences. No external commercial funding was received for this work.

Institutional Support

The authors thank the horticulture research farm staff of Windhoek Institute of Agricultural Sciences for maintaining irrigation infrastructure and trial plots across both seasons of this research.

Contributions Not Qualifying for Authorship

Soil temperature and moisture data logging equipment maintenance was supported by the Institute's soil science laboratory technical staff, whose assistance is gratefully acknowledged.

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