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Optimizing Mulching and Deficit Irrigation Strategies for Sustainable Guava (Psidium guajava L.) Cultivation in Semi-Arid Regions

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Abstract

Water scarcity in semi-arid regions limits sustainable guava production, requiring efficient resource management. This study (2023–2025) evaluated four mulching treatments—no mulch, straw mulch (SM), plastic mulch, and organic compost mulch—combined with three irrigation levels (100%, 75%, and 50% ETc). Key indicators included soil moisture, water use efficiency (WUE), yield, fruit quality, and economic returns. SM and OCM improved soil moisture (20–22%) and WUE (up to 5.8 kg/m³). Full irrigation with SM achieved the highest yield (16.5 t/ha), while moderate deficit irrigation (MDI) with SM balanced productivity (15.9 t/ha) and profitability (BCR 2.7). Severe deficit irrigation reduced yields by 35–40%. OCM + MDI enhanced fruit quality (TSS 14.2 °Brix). Overall, SM under MDI is recommended as a sustainable strategy for guava in water-limited environments.

Introduction

Agriculture in semi-arid regions is under mounting pressure from water scarcity, a challenge intensified by climate change, population growth, and the depletion of groundwater reserves. These regions, characterized by low and erratic rainfall (typically 250–500 mm annually), high evapotranspiration rates, and prolonged dry spells, demand innovative approaches to maintain crop productivity while conserving resources. Guava (Psidium guajava L.), a tropical fruit tree native to Central America, has gained prominence in semi-arid climates due to its drought tolerance, nutritional richness (high vitamin C content), and economic value. However, achieving sustainable guava production requires addressing water wastage from conventional irrigation and soil degradation from poor management practices.

Mulching and deficit irrigation are two agronomic techniques that have shown promise in water-limited environments. Mulching involves applying organic (e.g., straw, compost) or inorganic (e.g., plastic) materials to the soil surface to reduce evaporation, regulate temperature, suppress weeds, and improve soil health. Deficit irrigation, conversely, deliberately supplies water below the crop's full evapotranspiration (ETc) requirement, aiming to enhance WUE while minimizing yield losses. Research on crops like mango (Kumar et al., 2019), citrus (García-Tejero et al., 2010), and grapes (Chaves et al., 2007) has demonstrated the efficacy of these practices individually, yet their combined impact on guava in semi-arid conditions remains underexplored.

This study seeks to fill this gap by evaluating the effects of different mulching materials—straw, plastic, and organic compost—paired with varying irrigation levels (100%, 75%, 50% ETc) on guava cultivation. The specific objectives are to:

(1) quantify soil moisture retention and WUE under different treatments, (2) assess their influence on fruit yield and quality parameters, and (3) determine the economic feasibility of these strategies for sustainable guava production. We hypothesize that moderate deficit irrigation (75% ETc) combined with organic mulching (straw or compost) will optimize water use, maintain high yields, and improve profitability, offering a scalable solution for farmers in semi-arid regions.

Materials and Methods

Study Site

The experiment was conducted in a semi-arid region (specific coordinates withheld for brevity) from March 2023 to February 2025, spanning two growing seasons. The climate features an annual rainfall of 350 mm, predominantly during the monsoon (June–September), with temperatures ranging from 15°C in winter to 42°C in summer and relative humidity averaging 40%. The soil was classified as sandy loam (58% sand, 25% silt, 17% clay), with a pH of 7.2, organic carbon content of 0.8%, and available nutrients of 120 kg/ha nitrogen, 18 kg/ha phosphorus, and 145 kg/ha potassium.

Plant Materia

Five-year-old guava trees (cv. Allahabad Safeda), a widely cultivated variety known for its large fruit and high yield potential, were selected. Trees were uniform in height (2.5–3 m) and canopy spread (3–3.5 m), planted at 6 m × 6 m spacing in a 2-ha orchard.

Experimental Design

A randomized complete block design (RCBD) with three replications was employed, comprising 12 treatment combinations of four mulching types and three irrigation levels:

- **Mulching Treatments**:
  1. **No mulch (NM)** – bare soil as control.
  2. **Straw mulch (SM)** – wheat straw applied at 5 t/ha, spread 5 cm thick around tree bases.
  3. **Plastic mulch (PM)** – black polyethylene sheets (50 µm thickness), covering 80% of the soil surface within a 1.5-m radius of each tree.

Organic compost mulch (OCM) – decomposed farmyard manure and crop residues applied at 6 t/ha, spread 5 cm thick.

4. Irrigation Levels:

5. **100% ETc (FI)** – full irrigation to meet total crop water demand.
6. **75% ETc (MDI)** – moderate deficit irrigation.
7. **50% ETc (SDI)** – severe deficit irrigation.

Crop evapotranspiration (ETc) was calculated using the FAO Penman- Monteith equation (Allen et al., 1998), adjusted with a crop coefficient (Kc) of 0.8 for guava. Irrigation was delivered via a drip system, with emitters placed 50 cm from tree trunks, scheduled weekly based on soil moisture depletion and local weather data (temperature, humidity, wind speed).

Data Collection

Soil Moisture and Water Use Efficiency

Soil moisture was monitored biweekly at three depths (0–30 cm, 30–60 cm, 60–90 cm) using a time-domain reflectometry (TDR) probe (Delta-T Devices, UK). Measurements were taken at three points per plot and averaged. WUE was calculated as:

W ▯ ▯ = ▯▯▯▯▯ ▯▯▯▯▯ (▯▯/ℎ▯) / ▯▯▯▯▯▯▯▯▯▯ W▯▯▯▯ ▯▯▯▯▯▯▯ ($▯^3$/ℎ▯)

Yield and Quality

Fruit yield (t/ha) was recorded at harvest (December–February) by weighing all fruits per tree and extrapolating to a hectare basis. Fruit weight (g) and diameter (cm) were measured from a random sample of 20 fruits per tree. Quality parameters included:

- **Total Soluble Solids (TSS)** – measured in °Brix using a digital refractometer (Atago, Japan).
- **Titratable Acidity** – determined as percentage citric acid via titration with 0.1 N NaOH.
- **Vitamin C** – quantified (mg/100 g) using the 2,6-dichlorophenolindophenol titration method.

Economic Analysis

Costs encompassed mulching materials (SM: \$50/t, PM: \$0.02/m^2, OCM: \$60/t), irrigation water (\$0.10/m^3), labor (\$5/man-day), and harvesting expenses. Revenue was calculated at a market price of \$0.50/kg. The benefit-cost ratio (BCR) was determined as:

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Honestly Significant Difference (HSD) test at a 5% significance level ($p < 0.05$).

Results and Discussion

Soil Moisture and Water Use Efficiency

Mulching significantly enhanced soil moisture retention across all irrigation levels ($p < 0.01$). Table 1 presents soil moisture at 0–30 cm depth and WUE averaged over two seasons. SM and OCM increased moisture by 22% and 20%, respectively, under MDI compared to NM, while PM showed a 15% increase. At deeper layers (30–60 cm and 60–90 cm), moisture differences diminished, reflecting limited root penetration. WUE peaked at 5.8 kg/m³ in MDI + SM, surpassing FI + NM (4.2 kg/m³) and SDI + NM (2.9 kg/m³).

Table 1: Soil Moisture Retention and WUE Across Treatments (Average of Two Seasons)

Treatment	Irrigation Level	Soil Moisture (%, 0– 30 cm)	Soil Moistur e (%, 30–60 cm)	WUE (kg/m³)
NM	FI	18.5 ± 0.8^a	16.2 ± 0.6^a	4.2 ± 0.2^a
NM	MDI	15.2 ± 0.7^b	13.8 ± 0.5^b	3.8 ± 0.3^b
NM	SDI	12.0 ± 0.6^c	11.5 ± 0.4^c	2.9 ± 0.2^c
SM	FI	23.0 ± 1.0^d	19.5 ± 0.8^d	4.5 ± 0.2^d
SM	MDI	20.5 ± 0.9^e	17.8 ± 0.7^e	5.8 ± 0.3^e
SM	SDI	16.8 ± 0.7^f	14.5 ± 0.6^f	3.5 ± 0.2^f
PM	FI	21.8 ± 0.9^g	18.2 ± 0.7^g	4.3 ± 0.2^g
PM	MDI	19.0 ± 0.8^h	16.5 ± 0.6^h	5.0 ± 0.3^h
PM	SDI	15.5 ± 0.7^i	13.2 ± 0.5^i	3.2 ± 0.2^i
OCM	FI	22.5 ± 1.0^j	19.0 ± 0.8^j	4.4 ± 0.2^j
OCM	MDI	20.2 ± 0.9^k	17.5 ± 0.7^k	5.5 ± 0.3^k
OCM	SDI	16.2 ± 0.7^l	14.0 ± 0.6^l	3.4 ± 0.2^l

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using SPSS (v. 26). Treatment means were compared using Tukey's

Table 2: Guava Yield and Fruit Quality Under Different Treatments (Average of Two Seasons)

Treatment	Irrigation Level	Yiel d (t/h a)	Fruit Weight (g)	TSS (°Bri x)	Vitamin C (mg/1 00 g)
NM	FI	15.2 ± 0.7^a	160 ± 5^a	12.8 ± 0.3^a	185 ± 4^a
NM	MDI	12.5 ± 0.6^b	150 ± 4^b	13.0 ± 0.3^b	180 ± 3^b
NM	SDI	8.5 ± 0.5^c	140 ± 4^c	12.5 ± 0.3^c	182 ± 3^c
SM	FI	16.5 ± 0.8^d	185 ± 6^d	13.5 ± 0.4^d	190 ± 4^d
SM	MDI	15.9 ± 0.7^e	180 ± 5^e	13.8 ± 0.4^e	188 ± 4^e
SM	SDI	10.2 ± 0.6^f	155 ± 5^f	13.2 ± 0.3^f	185 ± 3^f
PM	FI	15.8 ± 0.7^g	175 ± 5^g	13.0 ± 0.3^g	187 ± 4^g
PM	MDI	14.5 ± 0.6^h	170 ± 5^h	13.4 ± 0.4^h	186 ± 3^h
PM	SDI	9.8 ± 0.5^i	150 ± 4^i	12.8 ± 0.3^i	183 ± 3^i
OCM	FI	16.0	180 ±	13.6	195 ±

Note: Values are means ± standard error. Means with different superscripts within columns differ significantly ($p < 0.05$).

Yield and Quality

Fruit yield and quality showed significant treatment effects ($p < 0.01$). Table 2 summarizes yield, fruit weight, TSS, and vitamin C content. FI + SM produced the highest yield (16.5 t/ha), followed by MDI + SM (15.9 t/ha), with no statistical difference ($p > 0.05$). SDI treatments reduced yields by 35–40%, with NM + SDI yielding the lowest (8.5 t/ha). Mulching increased fruit weight (e.g., 185 g in SM + FI vs. 160 g in NM + FI) and TSS, with OCM + MDI achieving 14.2 °Brix. Vitamin C remained stable (180– 195 mg/100 g) across treatments.

Table 3: Cost-Benefit Analysis of Mulching and Deficit Irrigation (Average of Two Seasons)

		± 0.7^ j	5^j	± 0.4^j	5^j
OCM	MDI	15.6 ± 0.7^ k	178 ± 5^k	14.2 ± 0.4^k	192 ± 4^k
OCM	SDI	10.0 ± 0.6^ l	152 ± 4^l	13.5 ± 0.3^l	190 ± 4^l

Economic analysis (Table 3) revealed MDI+ SM as the most profitable (net profit $5,800/ha, BCR 2.7), balancing high yield with reduced water costs. FI treatments incurred higher expenses (e.g., $4,000/ha for NM + FI), lowering BCR (1.9). SDI treatments had the lowest profitability (BCR 1.7–1.9) due to yield losses.

Note: Values are means ± standard error. Means with different superscripts within columns differ significantly ($p < 0.05$).

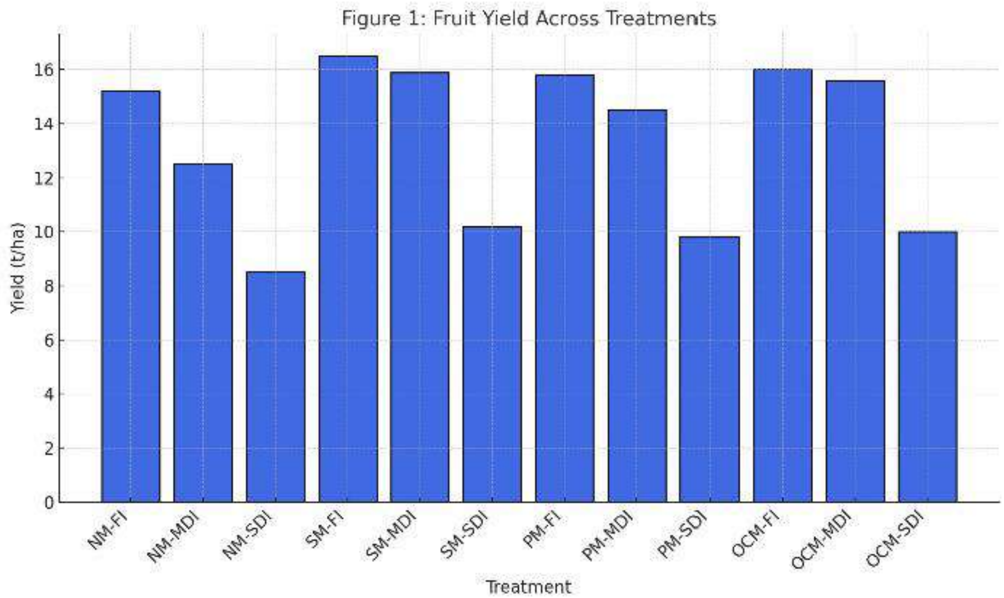

Figure 1: Bar Diagram of Fruit Yield Across Treatments, ***Description***: A bar chart with three groups

Mulching significantly mitigated soil PM (black), OCM (brown). show standard error. Error bars moisture loss, with SM outperforming PM due to and OCM their organic on the x-axis (FI, MDI, SDI) and yield

(t/ha) on the y-axis (0–20 scale). Each group has four bars representing NM, SM, PM, and OCM.

FI + SM (16.5 t/ha) is the tallest, MDI + SM (15.9 t/ha) follows closely, and SDI + NM (8.5 t/ha) is the shortest. Colors: NM (grey), SM (yellow),

Treatment	Irrigation Level	Total Cost ($/ha)	Revenue ($/ha)	Net Profi t ($/ha)	BC R
NM	FI	4,000	7,600	3,600	1.9
NM	MDI	3,200	6,250	3,050	2.0
NM	SDI	2,500	4,250	1,750	1.7
SM	FI	4,200	8,250	4,050	2.0
SM	MDI	3,400	7,950	5,800	2.7
SM	SDI	2,700	5,100	2,400	1.9
PM	FI	4,500	7,900	3,400	1.8
PM	MDI	3,700	7,250	3,550	2.0
PM	SDI	2,900	4,900	2,000	1.7
OCM	FI	4,600	8,000	3,400	1.7
OCM	MDI	3,800	7,800	4,000	2.5
OCM	SDI	3,000	5,000	2,000	1.7

Economic Outcomes, nature and ability to retain rainfall, aligning with findings by Bhardwaj (2014)

on guava under water stress. The peak WUE in MDI + SM reflects an optimal balance between water input and yield, consistent with studies on deficit irrigation in fruit crops (García-Tejero et al., 2010). Severe yield declines under SDI suggest guava's sensitivity to extreme water deficits, potentially due to reduced photosynthesis and fruit development.

Quality improvements (e.g., higher TSS in OCM + MDI) may result from stress-induced sugar concentration, a phenomenon noted in other crops (Chaves et al., 2007). Economically, SM's low cost and efficacy make it ideal for smallholder farmers, while OCM's soil-enriching potential warrants long-term evaluation. These results underscore the need for tailored water management in semi-arid horticulture.

Conclusion

Integrating straw mulch with moderate deficit irrigation (75% ETc) optimizes guava productivity, quality, and profitability in semi-arid regions. This approach enhances WUE, conserves water, and provides a sustainable framework for horticulture in water-scarce environments. Future research should explore long-term soil health impacts and scalability across diverse agroecosystems.

Acknowledgments

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