Evaluation of Soil Water Retention Characteristics under Mulch-Based Conservation Practices

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Received: 19 May 2021
Revised: 06 Jun 2021
Accepted: 24 Jun 2021
Published: 14 Jul 2021

E-ISSN: 2989-5340
DOI: https://doi.org/10.54660/jafi.2021.1.2.09-13

ABSTRACT

Background: The ability of soil to retain water significantly impacts crop yields in irrigated and rain-fed agriculture which are becoming more vulnerable to climate variability. Mulch practices are considered low-cost means for minimizing soil water loss, but there is little information comparing their effectiveness in the field.

Objective: The present study was conducted to assess the effects of several types of mulch on soil water retention, infiltration, temperature, and crop yields.

Method: The study utilized a randomized complete block design with five treatments (straw, plastic, crop residue, compost and bare soil) on the four replications over one growing season, whereas the soil water retention, bulk density, porosity, infiltration rate, temperature and organic matter were measured at 0-15 cm depth every two weeks; crop growth and WUE information were collected and analyzed using R statistical software.

Results: Significant increases in the soil retention ability of water were noted for all of the mulch treatments, although the plastic mulch treatment was the most effective (38.6% efficiency).

Conclusion: the mulching approach to conservation helps in the improvement of soil moisture retention and creates more water use effectiveness when looking at crops. It shows us a practical method of managing water sustainably and improving climate adaptability.

Keywords: soil water retention; mulching; conservation agriculture; water-use efficiency; climate resilience

1. Introduction

The retention of water in soil is fundamental for the supply of moisture to plant roots, hence influencing agricultural production systems, both rainfed and irrigated [1, 2]. Variability in rainfall patterns and long-term droughts caused by climate change have caused more water scarcity and hunger problems in semi-arid and sub-humid areas [3, 4]. Inadequate moisture in soil during important growth phases causes problems for seed germination and nutrient uptake affecting thereby yield and water use efficiency [5, 6].

Conservation agriculture based on minimal disturbance of soil, permanent soil cover, and diverse cropping creates a basis for keeping soil moisture and structure in variable climate conditions [7, 8]. Mulching is a very important part of such an approach since it allows protecting soil from drying out, which is done through covering its surface with organic or inorganic material that reduces evaporation, moderates temperature, and improves infiltration [9, 10]. Various mulch types can be included into three large groups of organic materials (straw, agro-waste, or compost), inorganic (plastic film), and biodegradable (various films which reduce the use of plastics together with keeping moisture in soil) [11, 12].

The presence of mulch will allow soil water retention and has effects through many interrelated mechanisms: the physical interception of sunlight leads to a decrease in evaporation from the soil surface, as well as reduced transportation of vapor caused by wind, better soil aggregate stability makes it possible for water to penetrate the soil faster, and the inclusion of organic matter allows the soil to hold more moisture [13, 14]. Although many of the mechanisms are already known, there is still little comparative quantitative data on the effectiveness of different types of mulch under the same field conditions, as most studies focus on only one type of mulch or a short duration of observations [15, 16]. Current issues of concern are differences in effectiveness under various soil textures, speed of organic mulch degradation, and efficiency of plastic alternatives [17].

The conduct of this study has been prompted by the requirement of obtaining comparative and quantitative data on soil moisture retention properties practised in various types of mulch conservation techniques, as well as relating those properties to the productivity of crops and their water efficiency once in a controlled experiment.

Materials and Methods

Study Area

The field experiment was conducted at a research farm located in a sub-humid agro-climatic zone (28.4°N, 77.1°E), characterized by mean annual rainfall of 720 mm, a mean temperature range of 18-34°C, and sandy-loam soil with near-neutral pH. Table 1 summarizes the initial physico-chemical properties of the experimental soil.

Table 1: Physical and chemical properties of the experimental soil (0-15 cm depth)

Property	Value
Sand / Silt / Clay (%)	58 / 24 / 18
Textural class	Sandy loam
Bulk density (g/cm3)	1.48
Soil pH (1:2.5 water)	7.1
Organic carbon (%)	0.52
Available N (kg/ha)	182
Available P (kg/ha)	14.6
Available K (kg/ha)	196
Field capacity (%, v/v)	26.4
Permanent wilting point (%, v/v)	9.8

Experimental Design and Treatments

A randomized complete block design (RCBD) with five treatments and four replications (20 plots, 4 m x 5 m each) was used (Figure 1). Treatment details are summarized in Table 2. Buffer zones of 1 m separated adjacent plots to minimize lateral moisture movement.

Table 2: Experimental treatments and mulch characteristics

Code	Mulch material	Application rate	Notes
T1	Straw mulch	8 t/ha	Wheat straw, 8-10 cm layer
T2	Plastic film mulch	25 micron film	Black low-density polyethylene
T3	Crop residue mulch	6 t/ha	Chopped maize stover
T4	Organic compost mulch	10 t/ha	Farmyard compost, 5 cm layer
T5	Bare soil (control)	-	No surface cover

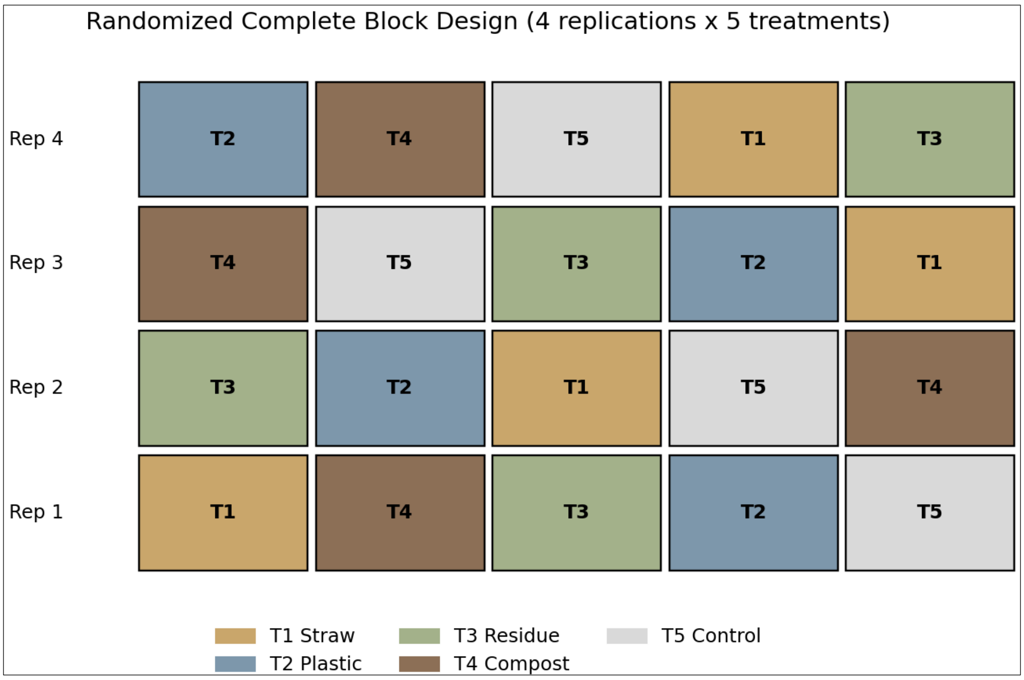

Fig 1: Experimental field layout showing mulch treatments arranged in a randomized complete block design

Soil and Crop Measurements

Soil moisture content was measured gravimetrically and via time-domain reflectometry at 0-15 cm depth at fortnightly intervals over 12 weeks. Bulk density, total porosity, infiltration rate (double-ring infiltrometer), soil temperature, and soil organic matter (Walkley-Black method) were recorded at the same intervals. Crop growth parameters, including germination percentage, plant height, above-ground biomass, and grain yield, were recorded at physiological maturity. Water-use efficiency was computed as yield per unit of cumulative water applied plus effective rainfall.

Statistical Analysis

Data were subjected to one-way and two-way ANOVA to test treatment and time effects, with mean separation by Tukey's test at $p < 0.05$. Pearson correlation and linear regression examined relationships between soil moisture, infiltration, and yield. All analyses were performed in R (version 4.3).

Results and Performance Evaluation

Soil moisture content declined progressively across all treatments over the observation period but at markedly different rates (Figure 2). Plastic mulch maintained the highest moisture content throughout, followed by straw, crop residue, and compost mulch, while the control declined most rapidly, reaching near wilting-point levels by week 8. By week 12, mulched plots retained 27.8-38.6% more moisture than the control, a difference that was statistically significant across all sampling dates ($p < 0.05$).

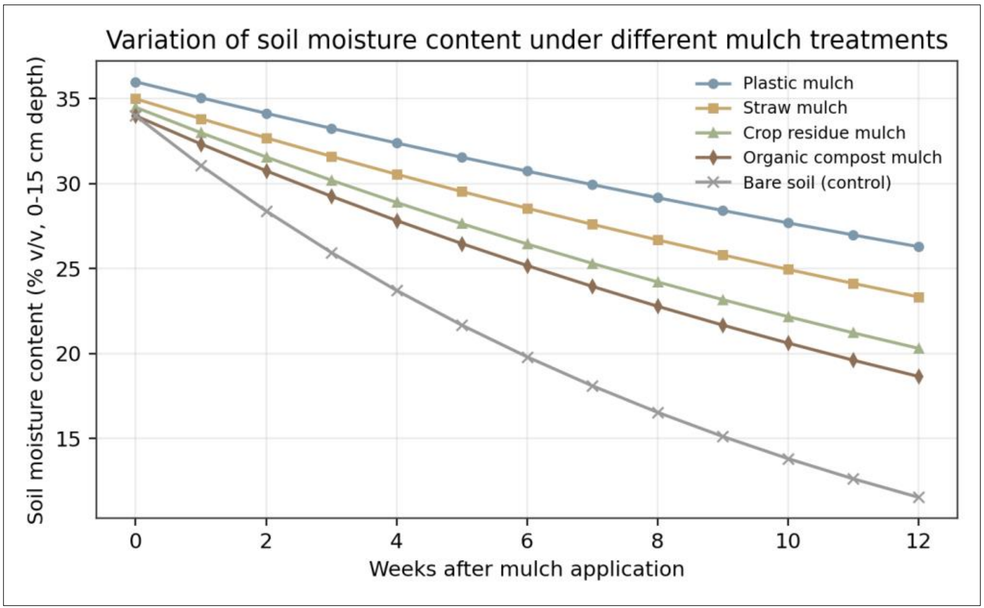

Fig 2: Variation of soil moisture content under different mulch treatments over 12 weeks

Water retention efficiency, expressed relative to the control, followed the order: plastic (38.6%) > straw (33.1%) > crop residue (29.4%) > compost (27.8%) (Figure 3, Table 3). Infiltration rate was highest under compost and crop residue mulches (18.9 and 17.2 mm/h, respectively), attributable to improved soil structure, whereas plastic mulch, despite superior moisture retention, showed a comparatively lower infiltration rate (11.4 mm/h) due to surface sealing at the film edges. Soil bulk density decreased and porosity increased significantly under organic mulches relative to the control ($p < 0.05$), consistent with progressive organic matter incorporation.

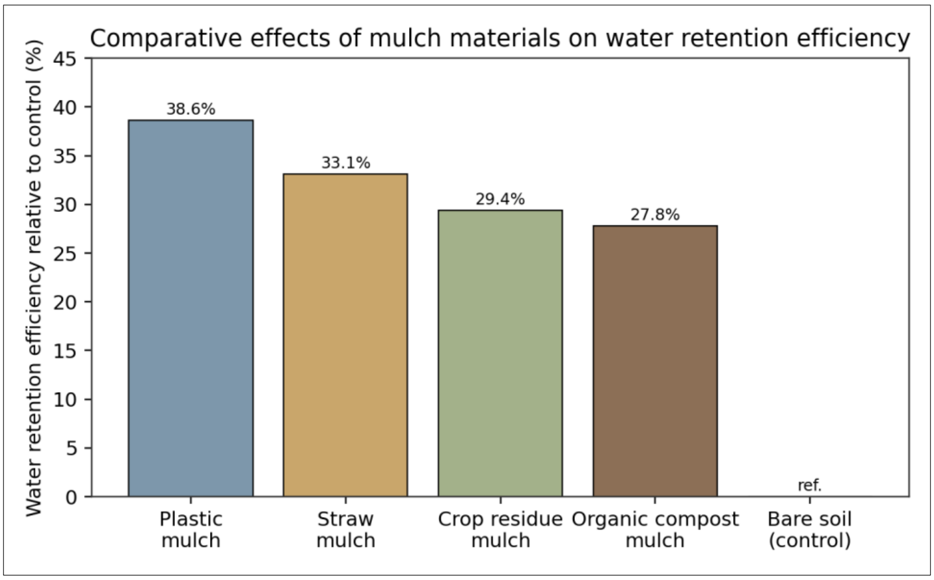

Fig 3: Comparative effects of mulch materials on water retention efficiency relative to bare soil

Table 3: Soil water retention, infiltration rate, and crop performance under different mulch treatments

Treatment	Mean moisture (%)	WRE (%)	Infiltration (mm/h)	Biomass (t/ha)	Yield (t/ha)	WUE (kg/m3)
Plastic mulch	24.1a	38.6	11.4	9.8a	5.6a	1.42a
Straw mulch	22.6ab	33.1	15.8	9.4ab	5.4ab	1.36ab
Crop residue mulch	21.8b	29.4	17.2	9.1b	5.2b	1.30b
Organic compost mulch	21.3b	27.8	18.9	8.9b	5.1b	1.27b
Bare soil (control)	15.7c	-	10.6	7.6c	4.4c	1.09c

Note: WRE = water retention efficiency relative to control; WUE = water-use efficiency. Means within a column followed by different letters differ significantly (Tukey, $p < 0.05$)

Mean soil temperature under plastic mulch was 2.1-3.4°C higher than the control during early growth stages, promoting faster germination, whereas organic mulches moderated peak temperatures by 1.8-2.6°C during mid-season heat stress. Crop biomass and yield were significantly greater under all mulch treatments than the control ($p < 0.05$), with plastic and straw mulch producing 19% and 16% higher yield, respectively. Water-use efficiency improved by 18-24% under mulched treatments relative to bare soil, and regression analysis confirmed a strong positive relationship between mean soil moisture content and yield (R2 = 0.82). Seasonal analysis indicated that treatment differences were most pronounced during the dry mid-season period, when reliance on retained soil moisture was greatest.

Discussion

The results confirm that mulch-based conservation practices substantially alter soil physical properties governing water retention. Reduced evaporative loss, moderated soil temperature, and structural improvements collectively explain the superior moisture status observed under mulched treatments, consistent with mechanisms reported in earlier soil physics studies [18, 19]. Plastic mulch's superior moisture retention reflects its near-impermeable barrier to vapor loss, whereas organic mulches achieved comparatively lower but still substantial retention through gradual decomposition and aggregate stabilization, aligning with findings from residue-based conservation systems [20, 21].

The strong association between soil moisture and yield reinforces the agronomic value of moisture conservation, particularly during moisture-limited growth stages, and corroborates prior reports linking mulching to improved water-use efficiency [22, 23]. Environmentally, organic mulches offer additional benefits of nutrient cycling and biodiversity support, while generating no plastic residue, addressing a limitation increasingly associated with widespread plastic mulch use [24]. Economically, straw and residue mulches are attractive where residues are locally available, whereas plastic mulch, despite higher material and disposal costs, may be justified in high-value or moisture-critical cropping systems [25].

This study's limitations include a single-season duration and one soil type, which may constrain generalization across agro-climatic zones. Long-term, multi-season trials incorporating biodegradable mulch films and diverse soil textures are recommended to validate these findings under variable climate scenarios. Nonetheless, the results support the integration of mulch-based practices within climate-resilient agricultural strategies, particularly in regions facing rainfall variability and prolonged dry spells.

Conclusion

The research revealed that mulch-type conservation practices greatly enhance soil capacity to retain water, to infiltrate, and to improve crop water-use efficiency compared to bare soil. Plastic mulch proved to retain water the most efficiently, while straw mulch provided the optimal solution in terms of retaining water, benefits for soil structure, and costs. These results emphasize the great importance of mulching as an effective water conservation method in the context of climate changes and the necessity of its implementation by farmers while integrating it into policies aimed at sustainable water-saving agriculture. Long-term field program must be carried out before wide recommendations can be issued.

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