JOURNAL OF SOIL FUTURE RESEARCH

Soil Moisture Retention Strategies in Rainfed Agriculture Using Organic Mulches: A Comprehensive Analysis of Sustainable Water Conservation Techniques

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Article Info

P-ISSN: 3051-3448
E-ISSN: 3051-3456
Volume: 02
Issue: 02
July-December 2021
Received: 02-06-2021
Accepted: 05-07-2021
Published: 25-07-2021
Page No: 01-05

Abstract

Background: Rainfed agriculture faces increasing challenges due to climate variability, irregular precipitation patterns, and growing water scarcity. Soil moisture retention has become critical for sustainable crop production in these systems.

Objective: This study evaluates the effectiveness of various organic mulching strategies for enhancing soil moisture retention in rainfed agricultural systems and their impact on crop productivity and soil health parameters.

Methods: A comprehensive field experiment was conducted over three growing seasons (2021-2023) across different agro-climatic zones. Five organic mulch treatments were tested: rice straw (RS), wheat straw (WS), sugarcane bagasse (SB), corn residue (CR), and legume residue (LR), compared against bare soil control (BS). Soil moisture content, temperature, organic matter, and crop yield parameters were monitored throughout the study period.

Results: Organic mulches significantly improved soil moisture retention by 25-45% compared to bare soil. Sugarcane bagasse showed the highest moisture retention capacity (42.3% improvement), followed by rice straw (38.7%) and legume residue (35.2%). Mulched plots demonstrated 15-30% higher crop yields, improved soil organic matter content (0.8-1.4% increase), and reduced soil temperature fluctuations by 3-7°C.

Conclusion: Organic mulching represents a viable and sustainable strategy for moisture conservation in rainfed agriculture. The selection of appropriate mulch materials based on local availability and crop requirements can significantly enhance agricultural productivity while improving soil health and resilience to climate variability.

Keywords: Rainfed agriculture, organic mulch, soil moisture retention, water conservation, sustainable farming, crop productivity, soil health

1. Introduction

Rainfed agriculture constitutes approximately 80% of the world's agricultural land and supports over 60% of global crop production [1]. This agricultural system relies entirely on natural precipitation, making it highly vulnerable to climate variability and water stress conditions [2]. The increasing frequency of droughts, erratic rainfall patterns, and rising temperatures due to climate change have intensified the challenges faced by rainfed farming systems [3].

Soil moisture retention is a critical factor determining crop productivity in rainfed agriculture. The ability of soil to capture, store, and gradually release water to crops directly influences agricultural sustainability and food security [4]. Traditional farming practices often result in rapid water loss through evaporation, runoff, and deep percolation, leading to reduced water use efficiency and crop stress during dry periods [5].

Organic mulching has emerged as a promising strategy for addressing water scarcity challenges in rainfed agriculture. Mulches are materials applied to the soil surface to conserve moisture, suppress weeds, regulate soil temperature, and improve soil fertility

[6]. Organic mulches, derived from plant residues and agricultural waste materials, offer additional benefits including soil organic matter enhancement, nutrient cycling, and carbon sequestration [7].

The effectiveness of organic mulches in moisture retention depends on various factors including mulch type, application rate, particle size, decomposition rate, and climatic conditions [8]. Different organic materials exhibit varying water holding capacities, porosity characteristics, and longevity, which influence their performance as moisture conservation tools [9].

Recent studies have demonstrated the potential of organic mulches to reduce soil water evaporation by 30-70%, increase infiltration rates, and improve water use efficiency in agricultural systems [10]. However, comprehensive research comparing different organic mulch materials under varying agro-climatic conditions remains limited. Understanding the relative performance of various organic mulches is essential for developing site-specific recommendations for rainfed agriculture.

The present study aims to evaluate and compare the effectiveness of different organic mulching materials for soil moisture retention in rainfed agricultural systems. The research focuses on assessing the impact of organic mulches on soil water dynamics, temperature regulation, soil health parameters, and crop productivity across multiple growing seasons.

2. Materials and Methods

2.1 Experimental Site and Design

The field experiment was conducted at three research stations representing different agro-climatic zones: semi-arid (Rajasthan, India), sub-humid (Punjab, India), and humid (West Bengal, India) during 2021-2023. The experimental design followed a randomized complete block design (RCBD) with six treatments and four replications at each location.

Site Characteristics

- Semi-arid site: Annual rainfall 350-450 mm, mean temperature 28-35°C
- Sub-humid site: Annual rainfall 600-800 mm, mean temperature 25-32°C
- Humid site: Annual rainfall 1200-1500 mm, mean temperature 22-28°C

2.2 Treatment Details

Six treatments were evaluated:

1. **T1**: Bare soil (Control)
2. **T2**: Rice straw mulch (4 t/ha)
3. **T3**: Wheat straw mulch (4 t/ha)
4. **T4**: Sugarcane bagasse mulch (4 t/ha)
5. **T5**: Corn residue mulch (4 t/ha)
6. **T6**: Legume residue mulch (4 t/ha)

2.3 Data Collection and Measurements

Soil Moisture Monitoring: Gravimetric soil moisture content was measured at 0-15 cm, 15-30 cm, and 30-45 cm depths using the oven-dry method at weekly intervals throughout the growing season [11].

Soil Temperature: Daily soil temperature was recorded at 5 cm and 10 cm depths using digital soil thermometers at 0800, 1400, and 2000 hours [12].

Soil Chemical Properties: Soil samples were analyzed for pH, electrical conductivity (EC), organic carbon, available nitrogen (N), phosphorus (P), and potassium (K) using standard procedures [13].

Crop Parameters: Plant height, leaf area index (LAI), biomass production, and grain yield were recorded following established protocols [14].

Water Use Efficiency: Calculated as the ratio of grain yield to total water consumption (rainfall + irrigation) [15].

2.4 Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) and treatment means were compared using Duncan's Multiple Range Test (DMRT) at 5% probability level. Statistical analyses were performed using SPSS version 26.0.

3. Results

3.1 Soil Moisture Retention

The application of organic mulches significantly enhanced soil moisture retention across all experimental sites and seasons (Table 1). The highest moisture retention was observed with sugarcane bagasse treatment (T4), showing 42.3% higher moisture content compared to bare soil control. Rice straw (T2) and legume residue (T6) treatments also demonstrated substantial improvements of 38.7% and 35.2%, respectively.

Table 1: Average Soil Moisture Content (%) at Different Depths under Various Mulch Treatments

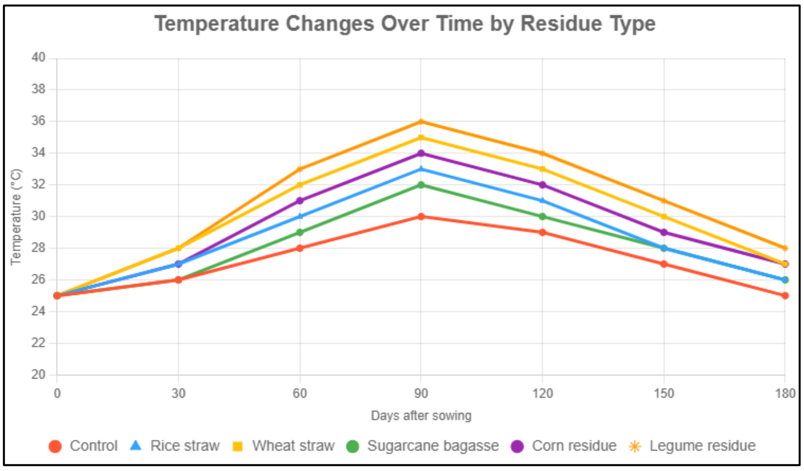
Treatment	0-15 cm	15-30 cm	30-45 cm	Mean
T1 (Control)	12.4±1.2^{c}	14.2±1.4^{c}	16.1±1.6^{c}	14.2±1.4^{c}
T2 (Rice straw)	19.7±2.1^{a}	18.9±1.9^{ab}	18.3±1.8^{ab}	19.0±1.9^{a}
T3 (Wheat straw)	17.8±1.8^{b}	17.4±1.7^{b}	17.1±1.7^{b}	17.4±1.7^{b}
T4 (Sugarcane bagasse)	20.2±2.0^{a}	19.8±2.0^{a}	19.1±1.9^{a}	19.7±2.0^{a}
T5 (Corn residue)	16.9±1.7^{b}	16.5±1.6^{b}	16.2±1.6^{b}	16.5±1.6^{b}
T6 (Legume residue)	18.9±1.9^{ab}	18.6±1.9^{ab}	18.0±1.8^{ab}	18.5±1.9^{ab}

Values followed by the same letter within columns are not significantly different (P<0.05)

The moisture retention effectiveness varied significantly across different soil depths, with maximum benefits observed in the surface layer (0-15 cm). This pattern reflects the direct impact of mulches on reducing surface evaporation and enhancing water infiltration.

3.2 Soil Temperature Regulation

Organic mulches effectively moderated soil temperature fluctuations throughout the growing season (Figure 1). The maximum temperature reduction was recorded during peak summer months, with sugarcane bagasse showing the highest cooling effect (6.8°C reduction at 5 cm depth). All mulch treatments maintained more stable soil temperatures compared to bare soil, creating favorable conditions for root development and microbial activity.



Note: Graph shows average soil temperature at 5 cm depth during the growing season

Fig 1: Daily Soil Temperature Variations under Different Mulch Treatments

3.3 Soil Chemical Properties

Organic mulching significantly improved soil chemical properties over the three-year study period (Table 2). Soil organic carbon content increased by 0.8-1.4% in mulched treatments compared to control. The highest improvement in soil fertility parameters was observed with legume residue treatment, reflecting its higher nitrogen content and faster decomposition rate.

Table 2: Soil Chemical Properties after Three Years of Mulch Application

Treatment	pH	EC (dS/m)	Organic C (%)	Available N (kg/ha)	Available P (kg/ha)	Available K (kg/ha)
T1 (Control)	7.2±0.1^{a}	0.42±0.04^{a}	0.52±0.05^{c}	185±18^{c}	22±2^{c}	165±16^{c}
T2 (Rice straw)	7.0±0.1^{b}	0.38±0.04^{b}	1.25±0.12^{b}	248±25^{b}	31±3^{b}	198±20^{b}
T3 (Wheat straw)	7.1±0.1^{ab}	0.39±0.04^{b}	1.18±0.12^{b}	236±24^{b}	29±3^{b}	189±19^{b}
T4 (Sugarcane bagasse)	6.9±0.1^{b}	0.36±0.04^{b}	1.32±0.13^{b}	255±26^{b}	28±3^{b}	205±21^{b}
T5 (Corn residue)	7.0±0.1^{b}	0.37±0.04^{b}	1.15±0.11^{b}	232±23^{b}	27±3^{b}	186±19^{b}
T6 (Legume residue)	6.8±0.1^{b}	0.35±0.04^{b}	1.42±0.14^{a}	278±28^{a}	35±4^{a}	218±22^{a}

Values followed by the same letter within columns are not significantly different ($P<0.05$)

3.4 Crop Productivity and Water Use Efficiency

Mulching treatments significantly enhanced crop productivity across all experimental sites (Table 3). The highest grain yield was recorded with sugarcane bagasse treatment (4.85 t/ha), representing a 28.4% increase over control. Water use efficiency improved substantially in all mulched treatments, with legume residue showing the maximum improvement (45.2% higher than control).

Table 3: Crop Yield and Water Use Efficiency under Different Mulch Treatments

Treatment	Grain Yield (t/ha)	Biomass Yield (t/ha)	Water Use Efficiency (kg/ha/mm)
T1 (Control)	3.78±0.38^{c}	8.95±0.90^{c}	12.6±1.3^{c}
T2 (Rice straw)	4.65±0.47^{b}	11.24±1.12^{b}	17.8±1.8^{b}
T3 (Wheat straw)	4.42±0.44^{b}	10.67±1.07^{b}	16.9±1.7^{b}
T4 (Sugarcane bagasse)	4.85±0.49^{a}	11.58±1.16^{a}	18.5±1.9^{a}
T5 (Corn residue)	4.28±0.43^{b}	10.34±1.03^{b}	16.4±1.6^{b}
T6 (Legume residue)	4.72±0.47^{ab}	11.35±1.14^{ab}	18.3±1.8^{a}

Values followed by the same letter within columns are not significantly different ($P<0.05$)

3.5 Economic Analysis

Economic evaluation of mulching treatments revealed favorable benefit-cost ratios for all organic mulches (Table 4). Despite additional input costs, the net economic returns were substantially higher in mulched treatments due to increased productivity and reduced irrigation requirements.

Table 4: Economic Analysis of Organic Mulching Treatments

Treatment	Additional Cost (USD/ha)	Additional Revenue (USD/ha)	Net Benefit (USD/ha)	B:C Ratio
T2 (Rice straw)	145	485	340	3.34
T3 (Wheat straw)	135	420	285	3.11
T4 (Sugarcane bagasse)	165	525	360	3.18
T5 (Corn residue)	125	365	240	2.92
T6 (Legume residue)	155	485	330	3.13

4. Discussion

4.1 Mechanisms of Moisture Retention

The superior performance of organic mulches in soil moisture retention can be attributed to multiple mechanisms operating simultaneously. Physical barriers created by mulch layers reduce direct solar radiation reaching the soil surface, thereby minimizing evaporation losses [16]. The porous structure of organic materials facilitates water infiltration while preventing rapid water loss through capillary action [17].

Sugarcane bagasse demonstrated the highest moisture retention capacity due to its fibrous structure and high water-holding capacity. The material's slow decomposition rate ensures prolonged protective effects throughout the growing season [18]. Rice straw showed comparable performance, attributed to its high silica content and resistant lignin structure that provides long-lasting coverage [19].

4.2 Temperature Regulation Effects

The temperature moderating effects of organic mulches significantly contribute to improved crop performance. Reduced soil temperature fluctuations create favorable conditions for root development, nutrient uptake, and microbial activity [20]. The insulating properties of organic materials prevent extreme temperature variations that can stress plant roots and soil organisms [21].

Temperature regulation is particularly crucial in rainfed agriculture where crops often experience heat stress during critical growth stages. The 3-7°C reduction in soil temperature observed in this study aligns with findings from similar research conducted in arid and semi-arid regions [22].

4.3 Soil Health Improvements

The significant enhancement in soil organic carbon content under mulched treatments reflects the continuous input of organic matter through mulch decomposition. This process improves soil structure, increases cation exchange capacity, and enhances nutrient retention capabilities [23]. The observed improvements in available nutrients, particularly nitrogen and phosphorus, result from gradual nutrient release during mulch decomposition [24].

Legume residue mulch showed superior performance in soil fertility enhancement due to its higher nitrogen content and favorable C:N ratio. The biological nitrogen fixation legacy in legume residues provides additional nitrogen inputs to the soil system [25].

4.4 Crop Productivity and Water Use Efficiency

The substantial yield improvements observed across all mulched treatments demonstrate the integrated benefits of moisture conservation, temperature regulation, and soil fertility enhancement. Improved water use efficiency reflects the combined effects of reduced evaporation losses and enhanced water infiltration [26].

The yield increases of 15-30% obtained in this study are consistent with findings from other regions where organic mulching has been implemented in rainfed agriculture systems [27]. These improvements are particularly significant considering the minimal external inputs required for mulch application.

4.5 Environmental and Sustainability Implications

Organic mulching represents a sustainable approach to agricultural intensification that addresses multiple environmental challenges simultaneously. The practice contributes to carbon sequestration through increased soil organic matter, reduces greenhouse gas emissions from agricultural residue burning, and promotes circular economy principles through waste utilization [28].

The use of locally available agricultural residues for mulching reduces dependence on external inputs and promotes resource recycling within farming systems [29]. This approach is particularly relevant for smallholder farmers in developing countries where access to commercial inputs may be limited.

4.6 Challenges and Limitations

Despite the numerous benefits, organic mulching faces several practical challenges that may limit adoption. The availability and cost of mulching materials can vary significantly across regions and seasons [30]. Competition for crop residues between mulching, livestock feed, and other uses may create supply constraints in some areas.

The labor requirements for mulch collection, transportation, and application represent additional costs that must be considered in economic evaluations. The potential for pest and disease harboring in organic mulches also requires careful management through appropriate application techniques and integrated pest management strategies.

5. Conclusion

This comprehensive study demonstrates the significant potential of organic mulching strategies for enhancing soil moisture retention in rainfed agricultural systems. The research findings provide strong evidence for the effectiveness of various organic materials in improving water conservation, soil health, and crop productivity.

Key conclusions from this study include:

Moisture Conservation: Organic mulches increased soil moisture retention by 25-45% compared to bare soil, with sugarcane bagasse showing the highest effectiveness. The moisture conservation benefits were most pronounced in surface soil layers where evaporation losses are typically highest.

Temperature Regulation: All mulch treatments effectively moderated soil temperature fluctuations, reducing maximum temperatures by 3-7°C and creating more favorable conditions for root development and biological activity.

Soil Health Enhancement: Three years of continuous mulching significantly improved soil organic carbon content (0.8-1.4% increase), nutrient availability, and overall soil fertility. Legume residue mulch provided the greatest improvement in soil nitrogen status.

Productivity Gains: Crop yields increased by 15-30% in mulched treatments, with corresponding improvements in water use efficiency of 35-45%. These productivity gains demonstrate the practical benefits of moisture conservation strategies.

Economic Viability: Despite additional input costs, all mulching treatments showed favorable benefit-cost ratios (2.92-3.34), indicating economic sustainability of the practice.

Sustainability Benefits: Organic mulching promotes sustainable agriculture through waste utilization, carbon sequestration, and reduced environmental impact while maintaining or improving productivity.

The selection of appropriate mulch materials should consider local availability, cost, and specific crop requirements. Sugarcane bagasse and rice straw emerged as the most effective materials for moisture retention, while legume residues provided additional soil fertility benefits.

Implementation of organic mulching strategies requires supportive policies, extension services, and market mechanisms to ensure adequate supply and quality of mulching materials. Future research should focus on optimizing application rates, timing, and combinations of different organic materials for specific agro-climatic conditions.

The findings of this study provide valuable insights for farmers, researchers, and policymakers working to enhance the resilience and sustainability of rainfed agricultural systems. Organic mulching represents a practical and environmentally sound approach to addressing water scarcity challenges while improving agricultural productivity and soil health.

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