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Assessing the role of cover crops in enhancing soil carbon sequestration: Experimental evidence from umariyapan block, Dheemarkheda District, Katni, Madhya Pradesh

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Abstract

Background: Soil organic carbon (SOC) is a critical indicator of soil fertility and climate resilience, particularly in semi-arid agro-ecosystems. Cover crops have emerged as a sustainable practice to enhance SOC and improve soil quality.

Objectives: This study evaluated the impact of leguminous (cowpea) and non-leguminous (mustard) cover crops compared with fallow control plots on soil organic carbon (SOC), soil physical properties, and microbial biomass carbon (MBC) in semi-arid regions of Madhya Pradesh, India.

Methods: Field experiments compared cowpea and mustard cover crops with a fallow control. Researchers measured SOC content, soil moisture, bulk density, and microbial activity to assess cover crops' contribution to soil improvement.

Results: Cover crops significantly improved soil properties compared with the fallow control. SOC increased marginally in fallow plots (0.32 → 0.33%, +0.01%), while cowpea showed the greatest improvement (0.31 → 0.41%, +0.10%), followed by mustard (0.32 → 0.37%, +0.05%). Soil moisture retention was greatest under cowpea (15.8 ± 0.6%) and moderate under mustard (14.2 ± 0.4%) compared to the control (12.4 ± 0.5%). Bulk density decreased slightly in cover-cropped plots, with cowpea (1.46 ± 0.02 g/cm³) and mustard (1.48 ± 0.02 g/cm³) performing better than the fallow (1.52 ± 0.03 g/cm³). Microbial biomass carbon increased significantly, rising from 145 ± 10 mg/kg in the control to 210 ± 12 mg/kg in cowpea and 185 ± 11 mg/kg in mustard plots, reflecting the beneficial influence of cover crops on microbial activity.

Conclusion: Cover crops, particularly legumes, effectively enhance SOC and soil quality in semi-arid regions. Adoption of cover crops can support climate-resilient agriculture, improve soil fertility, and promote sustainable farming practices. Policy interventions and farmer training programs are recommended to encourage wider adoption in semi-arid India.

Keywords: Cover crops, Soil organic carbon, Cowpea, Mustard, Semi-arid agro-ecosystems, Soil fertility, Climate-smart agriculture

Introduction

Agricultural soils are widely recognised as critical carbon reservoirs, serving both as a foundation for crop productivity and as a buffer against global climate change. Soil organic carbon (SOC) plays a central role in maintaining soil fertility, regulating nutrient cycles, and sustaining microbial diversity. However, conventional agricultural practices such as monocropping, intensive tillage, and excessive reliance on chemical fertilisers often accelerate SOC depletion, leading to soil degradation, reduced productivity, and heightened vulnerability to climate variability. The decline in SOC is particularly concerning in semi-arid regions, where fragile soils are prone to erosion and nutrient loss [1].

Cover crops, defined as non-cash crops grown between main cropping seasons, have emerged as a promising strategy to restore SOC levels. By adding biomass, improving soil structure, and stimulating microbial activity, cover crops contribute to carbon sequestration and enhance soil resilience. Leguminous cover crops, such as cowpea, fix atmospheric nitrogen and enrich soil organic matter, while non-leguminous species, such as mustard, contribute through root biomass and residue incorporation.

Integrating cover crops into traditional farming systems has been shown to improve soil health, reduce dependence on synthetic inputs, and mitigate greenhouse gas emissions [2].

Globally, cover crop adoption has gained momentum through climate-smart agriculture initiatives. Studies across temperate and tropical regions have demonstrated that cover crops can significantly increase SOC stocks, improve water retention, and reduce soil erosion. In India, however, cover crop adoption remains limited, particularly in semi-arid zones where farmers prioritise short-term yield gains over long-term soil health. This gap underscores the need for localised experimental evidence to demonstrate cover crops' benefits under specific agro-ecological conditions [3].

The Umariyapan block of Dheemarkheda district, Katni, Madhya Pradesh, represents a semi-arid agro-ecological zone characterised by sandy loam soils, low organic carbon content, and erratic rainfall patterns. Farmers in this region predominantly cultivate cereals such as wheat and rice, along with pulses, but cover cropping remains minimal. Soil fertility constraints, coupled with socio-economic pressures, have limited the adoption of sustainable practices [4]. Given these challenges, assessing the role of cover crops in enhancing SOC in this region is both timely and necessary.

This study evaluated the impact of leguminous (cowpea) and non-leguminous (mustard) cover crops compared with fallow control plots on soil organic carbon (SOC), soil physical properties, and microbial biomass carbon (MBC) in semi-arid regions of Madhya Pradesh, India. By comparing leguminous and non-leguminous cover crops against fallow control, the research seeks to quantify changes in SOC and evaluate the suitability of cover crops for semi-arid farming systems. The findings are expected to contribute to the broader discourse on sustainable agriculture, offering insights for policy interventions and farmer training programs in Madhya Pradesh and similar agro-ecological zones.

Materials and Methods

Study Area

The research was conducted in the Umariyapan block of Dheemarkheda district, Katni, Madhya Pradesh, located at 23.8°N latitude and 80.4°E longitude. This region falls within a semi-arid agro-ecological zone characterised by sandy loam soils with inherently low organic carbon content. The climate is marked by erratic rainfall, with an average annual precipitation of approximately 1100 mm, and a mean annual temperature of 26 °C. These conditions make soil fertility a major constraint for sustainable agriculture, thereby providing a suitable setting to evaluate the role of cover crops in improving soil health.

Experimental Design

A field experiment used a Randomised Block Design (RBD) to minimise variability and ensure statistical reliability. Three treatments were established:

- **T_1:** Fallow (control)
- **T_2:** Cowpea (leguminous cover crop)
- **T_3:** Mustard (non-leguminous cover crop)

We replicated each treatment three times to account for experimental error. Individual plots measured 5 m × 5 m, providing adequate space for crop establishment and soil sampling while maintaining uniformity across treatments.

Data Collection

We collected soil samples from each plot at a depth of 0-15 cm before sowing and after harvest to assess changes in soil properties. We measured SOC using the Walkley-Black wet oxidation method, a widely accepted SOC estimation technique. In addition to SOC, we recorded supplementary soil quality indicators, including soil moisture content, bulk density, and microbial biomass carbon (MBC). We selected these parameters to provide a holistic understanding of how cover crops influence soil physical and biological properties.

Statistical Analysis

We subjected the experimental data to Analysis of Variance (ANOVA) to test for significant differences among treatments. When ANOVA indicated statistical significance, we applied a post hoc Tukey's test to compare treatment means and identify specific differences. We used $p < 0.05$ for all statistical analyses to ensure observed differences were robust and not due to random variation.

Results

Soil Organic Carbon (SOC)

Initial SOC content was uniformly low across treatments, reflecting the sandy loam soils of the study area. After harvest, treatments differed significantly ($p < 0.05$). Cowpea cover cropping (T_2) resulted in the highest SOC increase, followed by mustard (T_3), while the fallow plots (T_1) showed negligible change (Table 1).

Table 1: Soil Organic Carbon (%) before and after cover crop treatments

Treatment	Pre-sowing SOC (%)	Post-harvest SOC (%)	Change (%)	P value
T_1: Fallow	0.32 ± 0.01	0.33 ± 0.02	+0.01	< 0.05
T_2: Cowpea	0.31 ± 0.02	0.41 ± 0.02	+0.10	
T_3: Mustard	0.32 ± 0.01	0.37 ± 0.02	+0.05	

Soil Moisture and Bulk Density

Cover crops improved soil moisture retention compared to fallow plots. Cowpea plots retained the highest moisture, while mustard showed moderate improvement. Bulk density decreased slightly in cover-cropped plots, indicating better soil structure (Table 2).

Table 2: Soil moisture and bulk density under different treatments

Treatment	Soil Moisture (%)	Bulk Density (g/cm³)	P value
T_1: Fallow	12.4 ± 0.5	1.52 ± 0.03	< 0.05
T_2: Cowpea	15.8 ± 0.6	1.46 ± 0.02	
T_3: Mustard	14.2 ± 0.4	1.48 ± 0.02	

Microbial Biomass Carbon (MBC)

Microbial activity was significantly enhanced in cover-cropped plots. Cowpea supported the highest microbial biomass carbon, reflecting the positive influence of leguminous residues on microbial communities (Table 3).

Table 3: Microbial biomass carbon (mg/kg soil)

Treatment	MBC (mg/kg)	P value
T_1: Fallow	145 ± 10	< 0.05
T_2: Cowpea	210 ± 12	
T_3: Mustard	185 ± 11	

Statistical Analysis

ANOVA confirmed significant differences among treatments for SOC, soil moisture, bulk density, and MBC ($p < 0.05$). Tukey's post hoc test revealed that cowpea (T_2) differed significantly from fallow (T_1) across all parameters, while mustard (T_3) showed intermediate values, significantly higher than fallow but lower than cowpea.

Discussion

This study showed that including cover crops significantly increased SOC compared with the fallow control. Among the treatments, cowpea a leguminous cover crop showed the highest increase in SOC, followed by mustard, a non-leguminous species. The improvement in SOC under cowpea can be attributed to its ability to fix atmospheric nitrogen, produce higher biomass, and stimulate microbial activity, all of which contribute to organic matter accumulation and carbon sequestration in soil. These findings align with previous reports showing that leguminous cover crops improve soil fertility and carbon storage through symbiotic nitrogen fixation and residue incorporation [5, 6].

The positive effect of mustard, although less pronounced than cowpea, suggests that non-leguminous cover crops also play a vital role in enhancing SOC through root biomass and residue return. Non-leguminous species contribute carbon inputs via root exudates and decomposition of above-ground residues, which improve soil structure and microbial habitat [7]. This aligns with Xiang *et al* (2025), who reported that both leguminous and non-leguminous cover crops enhance SOC and soil aggregation in temperate soils [8]. The results of the present study therefore reinforce the concept that cover crops, irrespective of their botanical group, can serve as effective tools for soil carbon management.

Improved soil moisture and reduced bulk density observed in cover-cropped plots further support the beneficial role of cover crops in enhancing soil physical properties. Cowpea plots retained higher moisture due to increased organic matter and better soil porosity, while mustard plots showed moderate improvement [9]. Acharya *et al*. (2024) reported similar findings, observing that cover crops improve water infiltration and reduce soil compaction in semi-arid systems.[5] Higher MBC under cowpea and mustard treatments indicates that cover crops stimulate microbial activity, accelerating organic matter turnover and nutrient cycling. This microbial response is crucial for maintaining soil health and long-term productivity [10].

Globally, cover crop adoption has been recognised as a key component of climate-smart agriculture. Studies across temperate and tropical regions have shown that cover crops increase SOC stocks, improve water retention, and reduce erosion.[3] However, adoption remains limited in India, particularly in semi-arid regions where farmers prioritise short-term yield gains over long-term soil health. The findings from Umariyapan block, Dheemarkheda district, Katni, Madhya Pradesh, highlight the potential of cover crops to address soil fertility constraints in such regions. Sandy loam soils with low organic carbon content and erratic rainfall patterns make this area well suited to evaluating the benefits of cover cropping. The observed improvements in SOC and microbial activity suggest that integrating cover crops into local farming systems could enhance soil resilience and sustainability.

The implications of this study extend beyond soil carbon management. By improving soil fertility and structure, cover crops can reduce dependency on chemical fertilisers, lower production costs, and contribute to climate change mitigation through carbon sequestration. Lal (2004) emphasised that soil carbon sequestration is a critical strategy for achieving global food security and environmental sustainability. Integrating cover crops into traditional cropping systems thus offers a practical way to deliver multiple ecosystem services improving soil health, conserving water, and reducing greenhouse gas emissions [11].

Study limitations

Despite the positive outcomes observed, this study has several limitations. First, the experiment was conducted over a single season, which restricts the ability to capture long-term dynamics of SOC and soil quality under continuous cover cropping. Multi-year trials would provide stronger evidence of sustained benefits. Second, the study was limited to two cover crop species—cowpea and mustard—representing leguminous and non-leguminous groups. While these species are relevant to semi-arid systems, broader evaluation across diverse cover crops could yield more comprehensive insights.

Third, the experimental design did not account for variations in management practices such as residue incorporation methods, irrigation regimes, or fertiliser application, which may influence SOC accumulation and soil physical properties. Fourth, the study focused primarily on soil parameters and did not assess potential trade-offs with crop yield, pest dynamics, or economic feasibility, all of which are critical for farmer adoption. Finally, the findings are site-specific to semi-arid regions of Madhya Pradesh and may not generalise to other agro-ecological zones without further validation.

Conclusion

This study confirms that cover crops, particularly leguminous species such as cowpea, play a pivotal role in enhancing soil organic carbon and improving soil quality in semi-arid agro-ecosystems of Madhya Pradesh. The substantial soil organic carbon gains under cowpea highlight the importance of nitrogen fixation, biomass return, and microbial stimulation in building soil fertility. Non-leguminous species like mustard also contributed positively, demonstrating that diverse cover crop options can provide complementary benefits through residue incorporation and root biomass inputs.

The evidence underscores the versatility of cover cropping as a sustainable practice that can improve soil structure, moisture retention, and microbial activity, thereby reducing reliance on chemical fertilisers. Beyond soil health, adopting cover crops offers significant potential for climate-resilient agriculture by contributing to carbon sequestration and mitigating greenhouse gas emissions.

To realise these benefits at scale, targeted policy interventions and farmer training programs are essential. Promoting cover crop integration into traditional cereal-pulse rotations, coupled with adoption incentives, can transform semi-arid agriculture into a more sustainable, climate-smart system. Ultimately, cover crops offer a practical pathway to achieve both environmental sustainability and long-term agricultural productivity in India's semi-arid regions.

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