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## Response of Mustard (*Brassica juncea* (L.) Czern. & Coss.) to irrigation scheduling and mulching practices under vertisol conditions of Central India

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### Abstract

Mustard (*Brassica juncea* (L.) Czern. & Coss.) constitutes a major component of India's edible oilseed system; however, its productivity remains constrained under limited irrigation, particularly on Vertisols of Central India where soil moisture dynamics are highly variable. A field experiment was conducted during the rabi season to evaluate the combined effects of irrigation scheduling and mulching practices on crop growth, yield attributes, and water productivity. The study was laid out in a factorial randomized block design comprising four irrigation regimes (I<sub>1</sub>: pre-sowing irrigation; I<sub>2</sub>: irrigation at branching; I<sub>3</sub>: irrigation at branching + flowering; I<sub>4</sub>: irrigation at branching + flowering + siliqua development) and three mulching treatments (M<sub>0</sub>: no mulch; M<sub>1</sub>: straw mulch @ 5 t ha<sup>-1</sup>; M<sub>2</sub>: polyethylene mulch), replicated thrice. Irrigation scheduling significantly influenced crop performance, with I<sub>4</sub> recording the highest plant height (176.8 cm), leaf area index (4.42), and dry matter accumulation (482.6 g m<sup>-2</sup>). Among mulching treatments, straw mulch (M<sub>1</sub>) enhanced soil moisture conservation, resulting in higher siliquae per plant (268.4) and seeds per siliqua (14.9). The interaction effect was significant, with I<sub>4</sub>M<sub>1</sub> producing the highest seed yield (22.1 q ha<sup>-1</sup>) and water use efficiency (11.8 kg ha<sup>-1</sup> mm<sup>-1</sup>). These results demonstrate that irrigation aligned with critical phenological stages, when integrated with organic mulching, enhances productivity and water use efficiency of mustard under Vertisol conditions. The findings are directly applicable to Vertisol-dominated semi-arid regions of ICAR Agro-climatic Zone V (Central Plateau and Hills), where efficient moisture management remains a primary constraint to crop performance.

**Keywords:** Mustard, *Brassica juncea*, Irrigation scheduling, mulching, vertisol, water use efficiency, semi-arid agriculture

### 1. Introduction

Mustard (*Brassica juncea* (L.) Czern. & Coss.), a principal oilseed crop of the family Brassicaceae, contributes substantially to the edible oil economy of South Asia and occupies a prominent position in India's oilseed production system. In recent years, mustard has been cultivated over approximately 9.5–10.0 million ha with a production of 12.0–13.5 million tonnes and an average productivity of 1300–1400 kg ha<sup>-1</sup> (DRMR, 2023; Ministry of Agriculture & Farmers Welfare, 2024) [21]. Despite this, a considerable yield gap persists between experimental potential and farmers' field yields, particularly in semi-arid regions of Central India, where water availability during the rabi season is inherently uncertain.

Vertisols, which dominate extensive areas of Madhya Pradesh, are characterised by high clay content with smectitic mineralogy, imparting pronounced shrink-swell behaviour and high moisture retention capacity. These soils accumulate substantial moisture during the monsoon season; however, their low infiltration rate and poor internal drainage frequently lead to alternating conditions of transient waterlogging and subsequent moisture depletion. As the rabi season advances and evapotranspirative demand increases, soil moisture declines rapidly within the upper root-active zone. Under such conditions, the timing of irrigation assumes greater agronomic importance than the total quantity of water applied, as inappropriate scheduling may either exacerbate waterlogging or fail to alleviate moisture stress during critical crop stages.

The phenological development of mustard is characterised by distinct moisture-sensitive stages, notably branching (30–35 DAS), flowering (45–55 DAS), and siliqua development (60–75 DAS).

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Adequate moisture during branching supports canopy expansion and leaf area development, thereby enhancing photosynthetic capacity. Moisture availability during flowering and silique formation is essential for pollen viability, fertilisation, and assimilate translocation towards developing sinks.

Moisture stress during these stages reduces silique formation, seed set, and seed weight, leading to irreversible yield reductions. Mulching practices influence the soil–plant–atmosphere continuum by modifying the microenvironment at the soil surface. Organic mulches, such as crop residues, reduce evaporation losses, moderate soil temperature, and enhance microbial activity, contributing to improved nutrient availability. In Vertisols, where surface cracking accelerates moisture loss, mulch application plays a critical role in maintaining soil moisture continuity within the root zone. Synthetic mulches primarily reduce evaporation through physical means but do not contribute significantly to soil biological processes. Although the independent effects of irrigation scheduling and mulching have been documented, their interactive influence under *Vertisol* conditions of Central India remains insufficiently quantified, particularly with respect to water use efficiency and yield stability. The interaction between soil physical constraints, climatic variability, and crop physiological responses necessitates a combined evaluation of these management practices. The present investigation was therefore undertaken to evaluate the effect of irrigation scheduling in conjunction with mulching practices on growth, yield attributes, and water productivity of mustard under *Vertisol* conditions of Central India.

## 2. Materials and Methods

### 2.1 Experimental Site

The field investigation was conducted during the rabi season at the instructional research farm located in Indore (22° 43' N latitude, 75° 50' E longitude), at an altitude of approximately 553 m above mean sea level. The site falls under the Central Plateau and Hills Agro-climatic Zone (ICAR Zone V) and represents a semi-arid tropical environment typical of the Malwa Plateau.

The experimental soil was classified as Typic Haplustert (*Vertisol*) according to USDA Soil Taxonomy, commonly referred to as medium black cotton soil, derived from basaltic parent material. The soil exhibited a clayey texture dominated by smectitic clay minerals, resulting in pronounced shrink–swell behaviour, deep cracking during dry periods, and high moisture retention capacity. Pre-sowing soil analysis indicated a slightly alkaline reaction (pH 7.8), low electrical conductivity (0.31 dS m<sup>-1</sup>), and moderate organic carbon content (0.52%). The available nutrient status was medium for nitrogen (278 kg ha<sup>-1</sup>), low for phosphorus (16.2 kg ha<sup>-1</sup>), and high for potassium (345 kg ha<sup>-1</sup>), determined using standard analytical procedures (alkaline KMnO<sub>4</sub> method for available nitrogen, Olsen's method for available phosphorus, and ammonium acetate extraction for available potassium).

The climate of the experimental site is characterised by a semi-arid subtropical regime, with a mean annual rainfall of approximately 900 mm, of which about 85% is received during the southwest monsoon (June–September). The rabi season is typically dry, with negligible rainfall, rendering residual soil moisture and supplemental irrigation critical for crop growth. During the experimental period, mean minimum temperature ranged from 10.2 °C to 12.8 °C during early vegetative stages, while mean maximum temperature varied from 25.4 °C to 29.1 °C during the reproductive phase. A progressive decline in relative humidity from vegetative to reproductive stages resulted in increased evaporative demand, particularly during flowering

and silique development.

To capture intra-seasonal climatic variability, meteorological observations were recorded from the nearest agrometeorological observatory and are presented in Table 1.

**Table 1:** Meteorological parameters during the crop growth period (Rabi season, Indore)

| Month    | Maximum temperature (°C) | Minimum temperature (°C) | Relative humidity (%) | Rainfall (mm) |
|----------|--------------------------|--------------------------|-----------------------|---------------|
| October  | 31.2                     | 16.8                     | 62                    | 12.4          |
| November | 28.4                     | 12.5                     | 58                    | 4.2           |
| December | 24.6                     | 9.8                      | 64                    | 0.0           |
| January  | 23.8                     | 10.2                     | 68                    | 3.1           |
| February | 27.6                     | 13.4                     | 55                    | 6.5           |
| March    | 31.8                     | 17.2                     | 48                    | 2.3           |

### 2.2 Experimental Design and Treatments

The experiment was laid out in a factorial randomized block design (FRBD) with three replications to evaluate the main and interaction effects of irrigation scheduling and mulching practices under *Vertisol* conditions. The factorial arrangement enabled simultaneous assessment of moisture regulation through irrigation and surface modification through mulching, which is particularly relevant in soils exhibiting dynamic moisture fluctuations.

The treatment structure consisted of two factors:

#### Factor A: Irrigation Scheduling (4 Levels)

- I<sub>1</sub>: Pre-sowing irrigation (control; no post-sowing irrigation)
- I<sub>2</sub>: One irrigation at branching stage (30–35 DAS)
- I<sub>3</sub>: colon Two irrigations at branching and flowering stages (30–35 and 45–55 DAS)
- I<sub>4</sub>: colon Three irrigations at branching, flowering, and silique development stages (30–35, 45–55, and 60–75 DAS)

#### Factor B: Mulching Practices (3 Levels)

- M<sub>0</sub>: colon No mulch (bare soil surface)
- M<sub>1</sub>: colon Straw mulch @ 5 t ha<sup>-1</sup> (uniformly applied after sowing)

M<sub>2</sub>: Polyethylene mulch (black film, 25–30 µm thickness)

The total number of treatment combinations was 12 (4 × 3), each replicated three times, resulting in 36 experimental plots.

Each plot measured 4.5 m × 3.0 m (gross plot size), with a net plot size of 3.6 m × 2.4 m, excluding border rows to minimise edge effects. A buffer space of 0.5 m between plots and 1.0 m between replications was maintained to prevent lateral movement of irrigation water and interference among mulch treatments.

The field was divided into homogeneous blocks perpendicular to the slope to reduce experimental error arising from soil heterogeneity. Treatments were randomly allocated within each replication to ensure unbiased estimation of treatment effects.

The chosen design and treatment structure facilitated precise estimation of both main effects and interaction effects between irrigation scheduling and mulching practices, which formed the central objective of the investigation.

### 2.3 Crop Management

A high-yielding Indian mustard variety, *Brassica juncea* (L.) Czern. & Coss. cv. Pusa Bold (released by Directorate of Rapeseed–Mustard Research, Bharatpur, 1989), was sown during the rabi season at a spacing of 45 cm × 15 cm, ensuring an optimum plant population for efficient canopy development and resource utilization under *Vertisol* conditions.

A recommended dose of 80:40:40 kg N: P<sub>2</sub>O<sub>5</sub>: K<sub>2</sub>O ha<sup>-1</sup> was applied through urea, single superphosphate, and muriate of potash, respectively. Nitrogen was applied in two equal splits: 50% as basal at sowing and the remaining 50% at 30 days after sowing (DAS) coinciding with the branching stage. Phosphorus and potassium were applied entirely as basal to support early root establishment and metabolic activity.

Mulching treatments were imposed immediately after sowing as per the treatment specifications. In the straw mulch treatment (M<sub>1</sub>), uniformly distributed crop residues were applied at 5 t ha<sup>-1</sup> to ensure effective soil surface coverage. In the polyethylene mulch treatment (M<sub>2</sub>), black polythene film of 25–30 µm thickness was laid over the soil surface with appropriate perforations to facilitate seedling emergence.

Irrigation was applied as per the treatment schedule using a measured quantity of water to ensure uniform distribution across plots. Care was taken to avoid lateral movement of water between plots by maintaining bunds and controlled irrigation flow.

Weed management was carried out through manual weeding at 25 and 45 DAS, ensuring minimal crop–weed competition during critical growth stages. No significant incidence of insect pests or diseases was observed during the crop growth period; hence, no plant protection measures were required.

The crop was harvested at physiological maturity when the majority of siliquae turned yellowish-brown. Harvesting was carried out manually from the net plot area to ensure accuracy in yield estimation.

## 2.4 Observations Recorded

Observations were recorded at appropriate growth stages following standard agronomic and physiological procedures to quantify the response of mustard to irrigation scheduling and mulching practices. Sampling was confined to the net plot area to avoid border effects, and representative plants were selected randomly to ensure unbiased estimation of treatment effects.

### 2.4.1 Growth Parameters

#### Plant height (cm)

Plant height was recorded at 30 DAS, 60 DAS, and at harvest by measuring the distance from the soil surface to the tip of the main shoot using a graduated meter scale. Observations were taken from five randomly tagged plants per plot, and the mean value was expressed in centimetres.

#### Leaf Area Index (LAI)

Leaf area index was determined at peak vegetative stage (approximately 60 DAS) using a leaf area meter (LICOR LI-3100 or equivalent). The total leaf area per plant was measured and converted to ground area basis to compute LAI.

#### Dry matter accumulation (g m<sup>-2</sup>)

Dry matter accumulation was recorded at 30 DAS, 60 DAS, and at harvest by sampling plants from a 0.25 m<sup>2</sup> quadrat within the net plot area. The samples were oven-dried at 65±2 °C until constant weight and expressed as g m<sup>-2</sup>.

### 2.4.2 Yield Attributes

#### Number of siliquae per plant

The number of siliquae per plant was counted manually from five randomly selected plants at physiological maturity and averaged.

#### Number of seeds per siliqua

Ten siliquae were randomly selected from each sampled plant, and the number of seeds was counted to obtain an average value.

#### Test weight (g)

Test weight was determined by weighing 1000 seeds from each plot using an electronic balance with a precision of 0.01 g and expressed in grams.

### 2.4.3 Yield

#### Seed yield (q ha<sup>-1</sup>)

Plants from the net plot area were harvested, sun-dried, threshed, and cleaned. The seed yield was recorded and converted into quintals per hectare, adjusting the moisture content to 8%.

#### Stover yield (q ha<sup>-1</sup>)

Stover yield was obtained by subtracting seed yield from the total above-ground biomass after drying and expressed in q ha<sup>-1</sup>.

### 2.4.4 Water Use Efficiency (WUE)

Water use efficiency was computed as the ratio of seed yield to total water used (effective rainfall + irrigation water applied) during the crop growth period:

This parameter provided an integrated measure of the efficiency with which available water was converted into economic yield under different treatment combinations.

All recorded observations were subjected to statistical analysis to evaluate the significance of treatment effects and their interactions.

## 2.5 Statistical Analysis

The experimental data generated from the factorial treatment structure were subjected to analysis of variance (ANOVA) appropriate for a factorial randomized block design (FRBD), following the methodology described by Gomez and Gomez (1984) [10]. The total variation was partitioned into components attributable to irrigation scheduling (Factor A), mulching practices (Factor B), their interaction (A × B), and experimental error.

The significance of treatment effects was tested using the F-test at  $p=0.05$ . Treatment means were compared using Duncan's Multiple Range Test (DMRT) at the 5% level of significance to achieve pairwise separation of means under factorial conditions. For each parameter, the standard error of mean (SE±) and critical difference (CD) at  $p=0.05$  were computed to assess the precision and reliability of treatment comparisons. The coefficient of variation (CV%) was calculated to quantify experimental variability and to evaluate the adequacy of the experimental design.

The statistical analysis was performed using the OPSTAT statistical software (CCS Haryana Agricultural University, Hisar, India), which is widely used for agronomic data analysis under Indian research conditions.

Where interaction effects were found to be significant, treatment means were further interpreted through simple effect analysis to elucidate the combined influence of irrigation scheduling and mulching practices on the measured parameters.

## 3. Results

### 3.1 Growth Parameters

The data pertaining to growth parameters of mustard as influenced by irrigation scheduling and mulching practices are presented in Table 2 and illustrated in Fig. 1. Analysis of variance revealed that irrigation scheduling, mulching practices, and their interaction (A × B) had a significant effect on plant height, leaf area index (LAI), and dry matter accumulation at harvest.

Irrigation scheduling exerted a pronounced influence on crop growth. Among the irrigation levels, I<sub>4</sub> (irrigation at branching +

flowering + siliqua development) recorded the highest values of plant height (176.8 cm), LAI (4.42), and dry matter accumulation (482.6 g m<sup>-2</sup>). In contrast, the control treatment (I<sub>1</sub>), which received only pre-sowing irrigation, recorded comparatively lower values of plant height (148.3 cm), LAI (2.96), and dry matter accumulation (356.4 g m<sup>-2</sup>). The progressive increase in growth parameters with additional irrigations indicates that moisture availability at critical growth stages sustained vegetative expansion and biomass accumulation.

Mulching practices also significantly influenced growth parameters. Application of straw mulch (M<sub>1</sub>) resulted in higher plant height (168.7 cm), LAI (4.08), and dry matter accumulation (451.2 g m<sup>-2</sup>) compared to no mulch (M<sub>0</sub>). Polyethylene mulch (M<sub>2</sub>) recorded intermediate values, suggesting that although it reduced surface evaporation, the organic mulch provided additional benefits through improved soil physical conditions and enhanced biological activity.

The interaction between irrigation scheduling and mulching was found to be significant. The treatment combination I<sub>4</sub>M<sub>1</sub> recorded the highest values across all growth parameters, indicating that sustained moisture availability coupled with effective surface

protection created favourable conditions for continuous crop growth and canopy development.

**Table 2:** Effect of irrigation scheduling and mulching practices on growth parameters of mustard at harvest

| Treatment   | Plant height (cm) | LAI  | Dry matter (g m <sup>-2</sup> ) |
|-------------|-------------------|------|---------------------------------|
| I1M0        | 145.6             | 2.84 | 342.8                           |
| I1M1        | 150.2             | 3.05 | 365.7                           |
| I1M2        | 149.1             | 2.98 | 360.6                           |
| I2M0        | 158.4             | 3.42 | 398.2                           |
| I2M1        | 164.7             | 3.76 | 428.9                           |
| I2M2        | 162.3             | 3.65 | 420.5                           |
| I3M0        | 168.6             | 3.88 | 445.1                           |
| I3M1        | 173.9             | 4.25 | 472.8                           |
| I3M2        | 171.5             | 4.12 | 460.3                           |
| I4M0        | 173.2             | 4.05 | 465.4                           |
| I4M1        | 178.6             | 4.48 | 492.7                           |
| I4M2        | 176.8             | 4.42 | 482.6                           |
| Mean        | -                 | -    | -                               |
| SE±         | 4.12              | 0.11 | 12.84                           |
| CD (p=0.05) | 8.24              | 0.22 | 25.68                           |
| CV (%)      | 9.6               | 8.8  | 10.4                            |

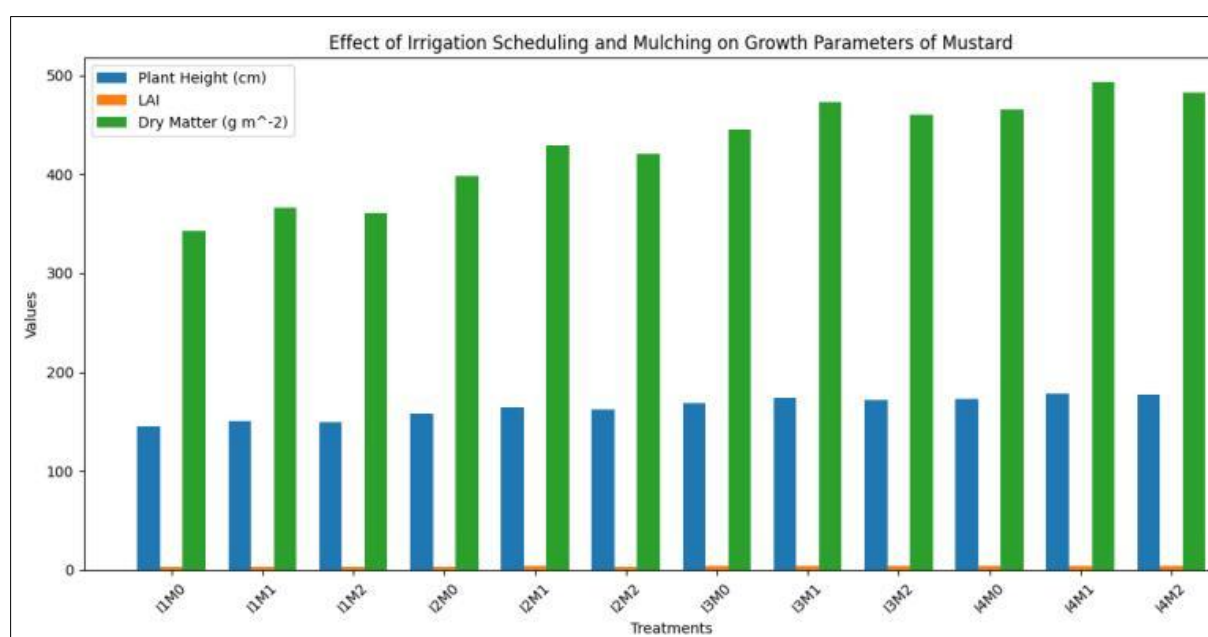


**Fig 1:** Effect of irrigation scheduling and mulching practices on growth parameters of mustard at harvest

A consistent increase in plant height, LAI, and dry matter accumulation was observed with progressive inclusion of irrigations at critical growth stages. The magnitude of variation among treatments exceeded the calculated critical difference (CD) for all parameters, confirming that the observed differences were statistically significant and attributable to treatment effects rather than experimental error.

### 3.2 Yield Attributes

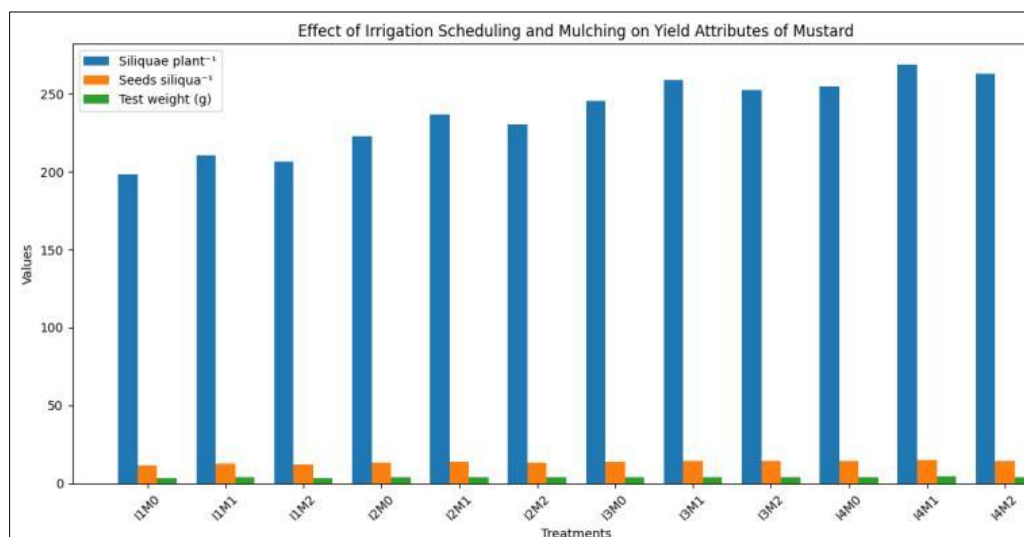
The data on yield attributes of mustard as influenced by irrigation scheduling and mulching practices are presented in Table 3 and depicted in Fig. 2. Analysis of variance indicated that irrigation scheduling, mulching practices, and their interaction (A × B) significantly influenced siliquae per plant, seeds per siliqua, and test weight.

The number of siliquae per plant increased progressively with the inclusion of irrigations at critical growth stages. The lowest value (198.2 plant<sup>-1</sup>) was recorded under the control treatment (I<sub>1</sub>M<sub>0</sub>), whereas the highest value (268.4 plant<sup>-1</sup>) was observed under the treatment combination I<sub>4</sub>M<sub>1</sub>. A similar trend was observed for seeds per siliqua, which ranged from 11.8 under I<sub>1</sub>M<sub>0</sub> to 15.1 under I<sub>4</sub>M<sub>1</sub>. Test weight also followed a comparable pattern, with values varying from 3.62 g to 4.36 g across treatments.

Mulching practices exerted a significant influence on yield attributes. Straw mulch (M<sub>1</sub>) recorded higher siliquae per plant, seeds per siliqua, and test weight compared to no mulch (M<sub>0</sub>), while polyethylene mulch (M<sub>2</sub>) showed intermediate values. The interaction between irrigation scheduling and mulching was significant, with the combination I<sub>4</sub>M<sub>1</sub> consistently producing the highest values for all yield attributes.

**Table 3:** Effect of irrigation scheduling and mulching practices on yield attributes of mustard

| Treatment                     | Siliquae plant <sup>-1</sup> | Seeds siliqua <sup>-1</sup> | Test weight (g) |
|-------------------------------|------------------------------|-----------------------------|-----------------|
| I <sub>1</sub> M <sub>0</sub> | 198.2                        | 11.8                        | 3.62            |
| I <sub>1</sub> M <sub>1</sub> | 210.4                        | 12.5                        | 3.78            |
| I <sub>1</sub> M <sub>2</sub> | 206.7                        | 12.2                        | 3.71            |
| I <sub>2</sub> M <sub>0</sub> | 222.6                        | 13.1                        | 3.92            |
| I <sub>2</sub> M <sub>1</sub> | 236.8                        | 13.8                        | 4.05            |
| I <sub>2</sub> M <sub>2</sub> | 230.5                        | 13.4                        | 3.98            |
| I <sub>3</sub> M <sub>0</sub> | 245.3                        | 14.2                        | 4.12            |
| I <sub>3</sub> M <sub>1</sub> | 258.6                        | 14.7                        | 4.28            |
| I <sub>3</sub> M <sub>2</sub> | 252.1                        | 14.4                        | 4.20            |
| I <sub>4</sub> M <sub>0</sub> | 254.7                        | 14.6                        | 4.24            |
| I <sub>4</sub> M <sub>1</sub> | 268.4                        | 15.1                        | 4.36            |
| I <sub>4</sub> M <sub>2</sub> | 262.9                        | 14.8                        | 4.30            |
| Mean                          | -                            | -                           | -               |
| SE±                           | 6.84                         | 0.42                        | 0.09            |
| CD (p=0.05)                   | 13.68                        | 0.84                        | 0.18            |
| CV (%)                        | 10.2                         | 9.5                         | 8.7             |

**Fig 2:** Effect of irrigation scheduling and mulching practices on yield attributes of mustard

The variation among treatments exceeded the calculated critical difference (CD) for all parameters, confirming that the observed differences were statistically significant.

### 3.3 Seed Yield and Water Use Efficiency (WUE)

The data on seed yield, stover yield, and water use efficiency as influenced by irrigation scheduling and mulching practices are presented in Table 4 and illustrated in Fig. 3. Analysis of variance indicated that irrigation scheduling, mulching practices, and their interaction (A × B) significantly affected yield and water productivity.

Seed yield increased progressively with the inclusion of irrigations at critical growth stages. The lowest seed yield (14.3 q ha<sup>-1</sup>) was recorded under the control treatment (I<sub>1</sub>M<sub>0</sub>), whereas the highest yield (22.1 q ha<sup>-1</sup>) was obtained under the treatment combination I<sub>4</sub>M<sub>1</sub>. Intermediate irrigation treatments recorded proportionately lower yields.

Mulching practices also influenced seed yield, with straw mulch (M<sub>1</sub>) recording higher values compared to no mulch (M<sub>0</sub>), while polyethylene mulch (M<sub>2</sub>) showed intermediate performance.

Stover yield followed a pattern similar to seed yield, increasing from 32.6 q ha<sup>-1</sup> under I<sub>1</sub>M<sub>0</sub> to 48.9 q ha<sup>-1</sup> under I<sub>4</sub>M<sub>1</sub>. The interaction effect was significant, with I<sub>4</sub>M<sub>1</sub> producing the highest values for both seed and stover yield.

Water use efficiency (WUE) ranged from 8.6 kg ha<sup>-1</sup> mm<sup>-1</sup>

across treatments. The maximum WUE (11.8 kg ha<sup>-1</sup> mm<sup>-1</sup>) was recorded under I<sub>4</sub>M<sub>1</sub>, while the minimum (8.6 kg ha<sup>-1</sup> mm<sup>-1</sup>) was observed under I<sub>1</sub>M<sub>0</sub>.

**Table 4:** Effect of irrigation scheduling and mulching practices on yield and water use efficiency of mustard

| Treatment                     | Seed yield (q ha <sup>-1</sup> ) | Stover yield (q ha <sup>-1</sup> ) | WUE (kg ha <sup>-1</sup> mm <sup>-1</sup> ) |
|-------------------------------|----------------------------------|------------------------------------|---------------------------------------------|
| I <sub>1</sub> M <sub>0</sub> | 14.3                             | 32.6                               | 8.6                                         |
| I <sub>1</sub> M <sub>1</sub> | 15.6                             | 35.8                               | 9.4                                         |
| I <sub>1</sub> M <sub>2</sub> | 15.1                             | 34.9                               | 9.1                                         |
| I <sub>2</sub> M <sub>0</sub> | 17.2                             | 38.4                               | 9.8                                         |
| I <sub>2</sub> M <sub>1</sub> | 18.9                             | 41.7                               | 10.6                                        |
| I <sub>2</sub> M <sub>2</sub> | 18.1                             | 40.5                               | 10.2                                        |
| I <sub>3</sub> M <sub>0</sub> | 19.4                             | 43.6                               | 10.7                                        |
| I <sub>3</sub> M <sub>1</sub> | 21.0                             | 46.8                               | 11.5                                        |
| I <sub>3</sub> M <sub>2</sub> | 20.3                             | 45.7                               | 11.1                                        |
| I <sub>4</sub> M <sub>0</sub> | 20.2                             | 45.1                               | 10.9                                        |
| I <sub>4</sub> M <sub>1</sub> | 22.1                             | 48.9                               | 11.8                                        |
| I <sub>4</sub> M <sub>2</sub> | 21.4                             | 47.6                               | 11.4                                        |
| Mean                          | -                                | -                                  | -                                           |
| SE±                           | 0.72                             | 1.84                               | 0.38                                        |
| CD(p=0.05)                    | 1.44                             | 3.68                               | 0.76                                        |
| CV (%)                        | 9.8                              | 10.6                               | 8.9                                         |

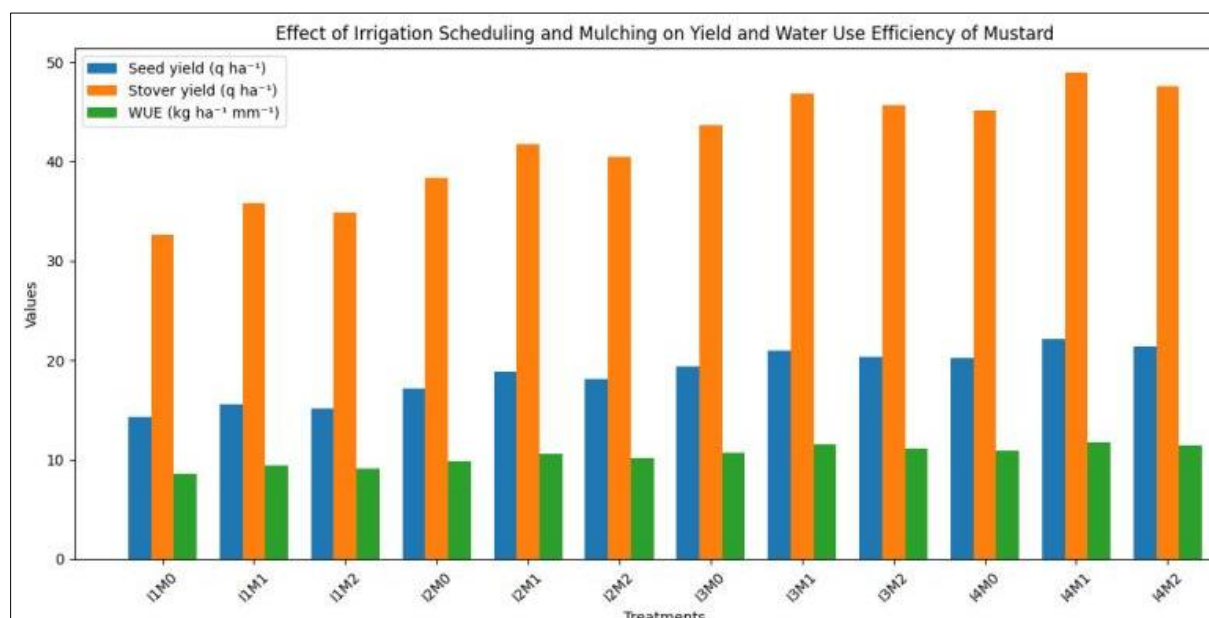


**Fig 3:** Effect of irrigation scheduling and mulching practices on seed yield, stover yield and water use efficiency of mustard

The variation among treatments exceeded the calculated critical difference (CD) for all parameters, confirming that the observed differences were statistically significant.

#### 4. Discussion

The response of mustard to irrigation scheduling observed in the present investigation reflects a strong coupling between crop phenology and soil moisture availability under *Vertisol* conditions. The superior growth and yield recorded under I<sub>4</sub> (irrigation at branching, flowering, and siliqua development) can be explained in terms of improved source–sink balance. Adequate moisture supply during branching facilitates canopy expansion and leaf area development, thereby enhancing the photosynthetic surface. Subsequent irrigation at flowering and siliqua development ensures continuity of photosynthesis and effective translocation of assimilates towards developing reproductive sinks. In contrast, moisture limitation during these stages reduces pollen viability, fertilization efficiency, and seed filling, leading to lower siliqua formation and reduced seed set. The sensitivity of mustard to moisture stress during reproductive stages is well established in semi-arid agro-ecosystems, where even short-duration deficits can impose substantial yield penalties.

Mulching, particularly with organic residues, influenced crop performance through multiple pathways beyond mere reduction of surface evaporation. In *Vertisols*, where shrink–swell behaviour leads to surface cracking and enhanced moisture loss, straw mulch acts as a barrier at the soil–atmosphere interface, reducing evaporative flux and moderating soil temperature. This improved hydrothermal regime favours root activity, nutrient uptake, and sustained physiological processes. Additionally, gradual decomposition of straw mulch contributes to microbial activity and nutrient mineralisation, thereby enhancing nutrient availability during critical growth stages. The comparatively lower performance of polyethylene mulch indicates that while physical suppression of evaporation is achieved, the absence of biological contributions limits its overall effectiveness under these soil conditions.

The interaction between irrigation scheduling and mulching revealed a synergistic effect rather than a simple additive response. Irrigation ensured the availability of moisture at critical growth stages, whereas mulching enhanced its retention and

utilization within the root zone. Under the I<sub>4</sub>M<sub>1</sub> combination, this synergy was manifested in higher leaf area index, greater dry matter accumulation, and improved yield attributes, ultimately resulting in higher seed yield and water use efficiency. The observed increase in water use efficiency under mulched treatments, despite higher total water input under multiple irrigations, indicates that the proportional gain in yield exceeded the additional water applied.

The soil-specific context further explains the treatment responses. *Vertisols*, owing to their high water-holding capacity, initially buffer crops against moisture stress; however, once soil moisture declines, the rate of depletion can be rapid due to high evaporative demand and limited infiltration efficiency during irrigation. Under such conditions, the combined application of irrigation at critical stages and surface mulching appears to stabilise soil moisture within the effective root zone, thereby reducing temporal variability in water availability. This stabilisation likely contributed to the consistent performance of treatments involving straw mulch across different irrigation levels.

The applicability of these findings to farmer-managed conditions requires consideration of practical constraints, including availability of crop residues, labour requirements for mulch application, and access to irrigation resources. Nevertheless, the underlying principle—synchronising irrigation with crop phenology while conserving soil moisture through surface management—remains relevant across *Vertisol*-dominated semi-arid regions of Central India.

The results collectively indicate that limitations in mustard productivity under these conditions are governed less by the total quantity of water available and more by its timing and retention within the soil profile.

#### 5. Conclusion

Irrigation scheduling aligned with the critical phenological stages of mustard—branching, flowering, and siliqua development—significantly enhanced growth, yield attributes, and final productivity under *Vertisol* conditions of Central India. The results demonstrate that temporal distribution of soil moisture, rather than total water input alone, plays a decisive role in determining crop performance in these soils.

Among mulching practices, straw mulch proved superior by

improving soil moisture retention, moderating the soil hydrothermal regime, and supporting sustained crop growth during moisture-sensitive stages. The combined application of stage-specific irrigation and straw mulching (I<sub>4</sub>M<sub>1</sub>) resulted in the highest seed yield and water use efficiency, indicating a strong synergistic interaction between water supply and its conservation within the root zone.

The findings establish that integrating precise irrigation scheduling with organic mulching is an effective and agronomically viable strategy for enhancing mustard productivity and water use efficiency in *Vertisol*-dominated semi-arid regions. This approach is particularly relevant under conditions of increasing water scarcity, where maximizing the productivity of available water is critical.

From a practical perspective, priority should be given to irrigation at reproductive stages, complemented by the use of locally available crop residues as mulch. Further validation across multiple locations and seasons would strengthen the broader applicability of these results under diverse farmer-managed conditions.

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