



RESEARCH ARTICLE

# Effects of irrigation frequency and mulching on maize growth and yield in a high-altitude semi-arid environment of Daykundi, Afghanistan

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Received: 14 February 2026; Accepted: 21 May 2026; Available online: Version 1.0: 31 July 2026

**Cite this article:** Yasin K, Mohammad HA, Nasrullah N, Habibullah P, Mohammad SM. Effects of irrigation frequency and mulching on maize growth and yield in a high-altitude semi-arid environment of Daykundi, Afghanistan. *Plant Science Today* (Early Access). <https://doi.org/10.14719/pst.14099>

## Abstract

Water scarcity is a major constraint to maize production in the high-altitude semi-arid regions of Afghanistan. This study investigated the combined effects of irrigation interval and mulch type on the growth, yield components and grain yield of the local maize cultivar Logari under high-altitude semi-arid conditions in Daikundi, Afghanistan. A split-plot randomised complete block design (RCBD) was implemented with three irrigation intervals (7, 10 and 14 days) as main plots and four mulch treatments (green plastic, transparent plastic, organic straw and no-mulch) as subplots, replicated three times ( $n = 36$  plots). Plant growth traits, yield components and grain yield were analysed using GLM split-plot ANOVA followed by LSD mean separation. Results demonstrated that mulch type significantly influenced all measured traits ( $p < 0.01$ ), whereas irrigation interval affected grain yield only ( $p < 0.05$ ). Green and transparent plastic mulches produced the highest grain yield ( $6.46 \text{ t ha}^{-1}$ ), approximately 40 % greater than organic mulch and no-mulch treatments ( $4.42\text{--}4.66 \text{ t ha}^{-1}$ ). Maize under 7- and 10-day irrigation intervals also produced significantly higher grain yield than the 14-day interval. Although the irrigation  $\times$  mulch interaction was not statistically significant, plastic mulch treatments maintained numerically higher yields under extended irrigation intervals. These findings indicate that plastic mulching can improve maize productivity and irrigation water productivity under semi-arid conditions. However, soil moisture, soil temperature and evapotranspiration were not directly measured. Further studies incorporating direct soil-water monitoring and biodegradable mulch alternatives are recommended.

**Keywords:** irrigation interval; plastic film mulch; semi-arid environment; water productivity; yield components

## Introduction

Maize (*Zea mays* L.) is one of the world's principal cereal crops, underpinning food security, animal feed systems and numerous industrial applications owing to its high photosynthetic efficiency as a C4 species (1, 2). In Afghanistan, maize is among the major crops an annual production of 0.11 million tonnes production and average yield  $2.7 \text{ t ha}^{-1}$  (3, 4). Yield formation in maize is strongly dependent on water availability, with vegetative growth, anthesis and silking and grain filling identified as particularly sensitive phenological phases during which water deficits markedly reduce biomass accumulation and final grain yield (5). In arid and semi-arid agro ecosystems, limited and erratic precipitation combined with elevated evapotranspiration rates frequently constrain plant-available soil moisture and thereby limit maize yield potential (6, 7). Ongoing climatic shifts are projected to exacerbate both the frequency and severity of water stress events, increasing the urgency of developing water-conserving agronomic practices that sustain productivity under constrained water supplies (8).

Irrigation scheduling is a central management lever for reconciling crop water demand with scarce water resources. While frequent irrigation can maintain favorable soil moisture and support physiological processes such as photosynthesis and nutrient uptake, longer irrigation intervals may be required where water is limited, with attendant risks of reduced growth and yield (9). Consequently, identifying irrigation regimes that optimise the trade-off between water savings and acceptable crop performance is a priority for semi-arid agriculture and requires integrated evaluation of crop responses across growth stages and environmental contexts (10).

Soil mulching using organic residues or synthetic films to cover the soil surface has been widely adopted to reduce non-productive soil evaporation, moderate soil temperature, suppress weeds and improve near-surface soil physical properties, collectively enhancing water use efficiency and crop performance (11–13). Empirical studies and syntheses indicate that plastic mulches, particularly polyethylene films, often produce larger increases in soil moisture conservation and maize yield than organic mulches, although crop-residue mulches can confer additional benefits for soil fertility and long-term soil health (14, 15). Moreover, several

investigations report synergistic effects when mulching is combined with deficit or optimised irrigation schedules, yielding improvements in photosynthetic capacity, dry matter accumulation and water use efficiency relative to bare-soil, conventionally irrigated systems (8, 15–17).

Despite a substantial body of work on irrigation and mulching in many agroecological zones, there is a paucity of empirical evidence from high-altitude semi-arid environments such as Ghudar, Daikundi Province, Afghanistan, where maize remains an important subsistence and market crop but where local climatic and edaphic conditions may alter crop responses to water management and mulching (13, 18). In these systems, traditional bare-soil practices can lead to high evaporative losses and inefficient water use; therefore, locally derived data are needed to inform context-specific recommendations that reconcile water conservation with yield stability.

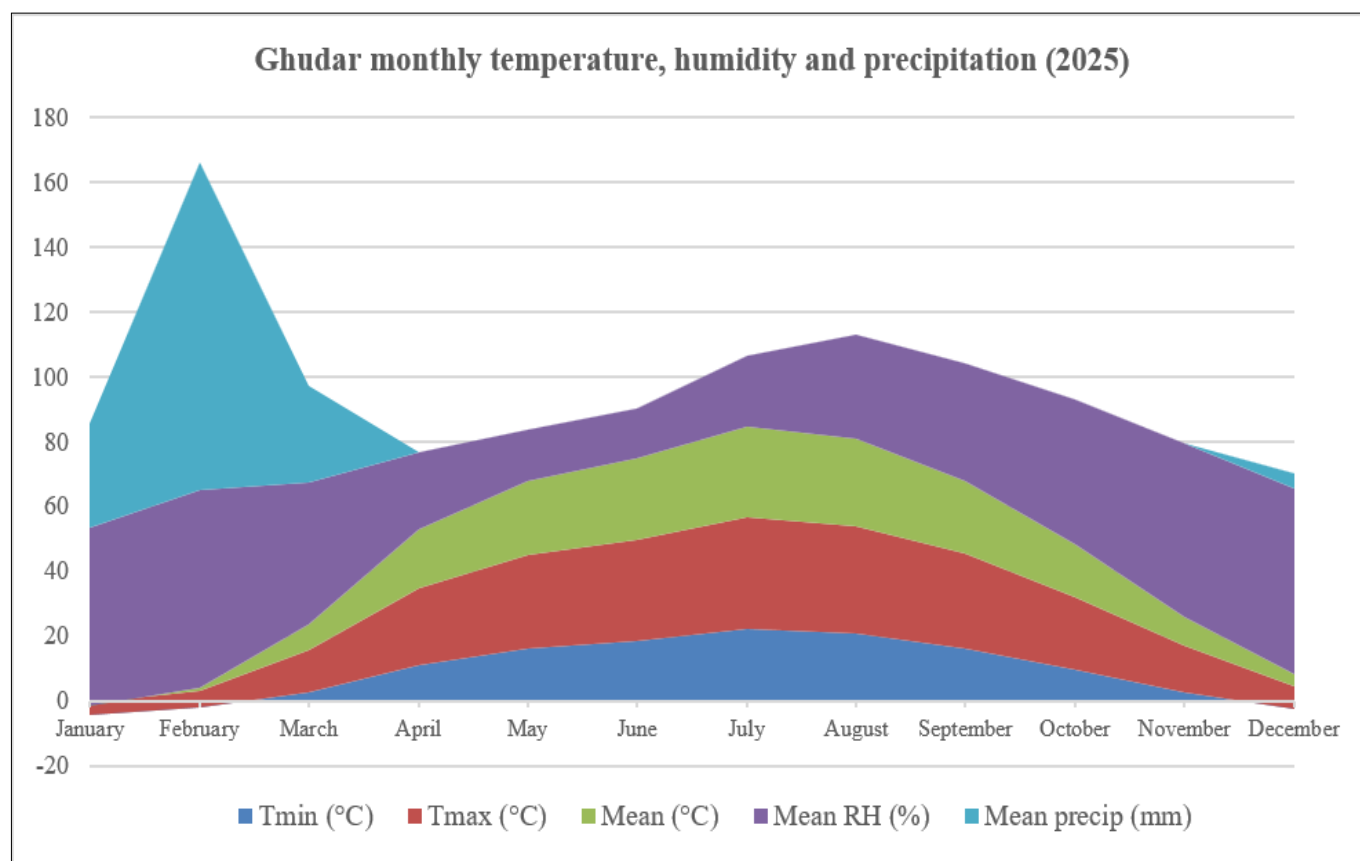
This study therefore evaluated the effects of three irrigation intervals (7, 10 and 14 days) and four mulching treatments: green plastic mulch (GPM), transparent plastic mulch (TPM), organic mulch (maize straw) and a no-mulch (NM) control on morphological traits, yield components and grain yield of the local maize cultivar ‘Logari’ under the agro-climatic conditions of Ghudar, Daikundi Province. Previous researchers aimed to quantify maize growth and yield responses to combined irrigation interval and mulch treatments (1), assess treatment effects on water use efficiency based on irrigation frequency/interval (2) and generate evidence-based recommendations for irrigation and mulching practices that enhance maize productivity and sustainable water use in high-altitude semi-arid environments (3).

## Materials and Methods

### Experimental site and design

The field experiment was conducted during the 2025 maize growing season at the experimental farm in Ghudar (Nili district), Daikundi Province, Afghanistan (33.6482° N, 66.1628° E; elevation 2020 m above sea level). The study area is characterised by a semi-arid high-altitude climate with cold winters, warm dry summers and low, unevenly distributed precipitation. Maize production in the region depends primarily on supplemental irrigation due to limited rainfall during the growing season. Long-term agro-meteorological data for the study area are summarised in Fig. 1. Mean monthly temperature ranged from -1.1 °C in January to 28.1 °C in July, with an annual mean temperature of approximately 15.0 °C. Mean relative humidity ranged from 15 to 61 %, while total annual precipitation was approximately 168.3 mm, most of which occurred during winter and early spring. No substantial rainfall occurred during the maize growing season (May–September), indicating a strong dependence on irrigation water for maize production under local conditions.

Prior to sowing, composite soil samples (0–30 cm depth) were collected from the experimental field for basic physicochemical characterisation. Soil texture was estimated using a sedimentation method under laboratory conditions by mixing soil samples with water in graduated cylinders and allowing particles to settle for 24 hr. Based on the average of three representative samples, the soil contained approximately 29 % sand, 32 % silt and 39 % clay, corresponding to a clay-loam texture. Soil pH was measured using a digital pH meter and recorded as 7.6. Due to limited laboratory facilities and analytical resources available during the study period, detailed analyses of soil organic matter and nutrient concentrations [nitrogen (N), phosphorous (P) and potassium (K)] were not performed.



**Fig. 1.** Monthly long term meteorological averages for Ghudar during 2025: minimum, maximum, mean temperature, relative humidity and precipitation.

Prior to sowing, the field was ploughed, leveled and cleared and the previous crop was clover (*Trifolium repens* L.).

### Experimental design and treatments

A split-plot arrangement within a randomised complete block design (RCBD) with 3 replications was used. Main plots were irrigation interval treatments: 7 days, 10 days and 14 days. Subplots were mulch treatments: Transparent plastic mulch (TPM), green plastic mulch (GPM), organic mulch (OM; maize straw) and no mulch (NM; control). Each subplot measured 2 × 2 m (4 m<sup>2</sup>). Plots were separated by a 50-cm buffer to minimise lateral movement of water and nutrients. The experiment comprised 36 experimental units (3 replications × 3 irrigation levels × 4 mulch types).

### Plant material and crop management

The local maize cultivar ‘Logari’ was sown on 27 May 2025. Planting geometry was 50 cm row spacing and 25 cm intra-row spacing; two to three seeds were placed per hill and later thinned to one plant per hill to achieve uniform stand density. Fertiliser was applied uniformly to all plots at rates equivalent to 100 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> and 150 kg N ha<sup>-1</sup>. Standard agronomic practices for weed, pest and disease control were applied uniformly across all treatments.

### Irrigation and mulching procedures

Irrigation was applied by furrow using a one-inch outlet with an average discharge of 0.769 L sec<sup>-1</sup> (10 L every 13 sec). Each irrigation event lasted 45–50 min, delivering about 2.19 m<sup>3</sup> to the 12 plots irrigated simultaneously, which equals ≈ 0.183 m<sup>3</sup> per plot. Because each plot measured 4 m<sup>2</sup>, this volume corresponds to an irrigation depth of 45.7 mm per application (equivalent to 457 m<sup>3</sup> ha<sup>-1</sup> per event). The three irrigation schedules received different numbers of events over the season: 14 events for the 7-day interval, 11 events for the 10-day interval and 9 events for the 14-day interval. Cumulative seasonal water applications were therefore ≈ 6398 m<sup>3</sup> ha<sup>-1</sup> (7-day), ≈ 5027 m<sup>3</sup> ha<sup>-1</sup> (10-day) and ≈ 4113 m<sup>3</sup> ha<sup>-1</sup> (14-day).

Mulches were applied immediately after sowing and kept in place until harvest. The TPM and GPM were laid as continuous sheets with planting holes for seedlings. The OM consisted of locally sourced maize straw spread to a thickness of 2–3 cm to ensure full soil cover. No-mulch (NM) plots were left bare.

### Crop measurements

Growth and morphological traits. At 12 weeks after sowing, plant height was measured from the soil surface to the tip of the tassel on four randomly selected plants per subplot. Stem diameter was measured at the basal internode of the same plants using a Vernier caliper. Number of leaves per plant was recorded at approximately 80 days after sowing on the same representative plants. Yield components and grain yield. At physiological maturity, number of cobs per plant was recorded from four plants per subplot. Cob length and cob diameter were measured on four randomly selected cobs per subplot using a ruler and Vernier caliper, respectively. 100-seed weight was determined in triplicate from sun-dried kernels

sampled from each subplot. Grain yield per subplot was obtained by harvesting all cobs from the subplot, sun-drying for eight days to a consistent moisture level, shelling and weighing with a precision balance; yield was converted to t ha<sup>-1</sup> for reporting. All measurements were performed using calibrated instruments and standardised protocols to ensure repeatability.

### Data handling and statistical analysis

All data were checked for entry errors and screened for adherence to ANOVA assumptions. Normality of residuals and homogeneity of variances were assessed using the Shapiro–Wilk test and Levene’s test, respectively; all measured variables met these assumptions. A split-plot analysis of variance (ANOVA) appropriate for a RCBD with split-plots was performed using the general linear model (GLM) procedure in IBM SPSS Statistics v.27. The experimental design included irrigation interval (main-plot: 7, 10, 14 days) and mulch type (subplot: TPM, GPM, OM, NM) with 3 replications (total experimental units, n = 36). The ANOVA results are reported based on mean squares and F-tests; effects were considered significant at  $p < 0.05$ . Where factors or interactions were significant, pairwise mean comparisons were conducted using the least significant difference (LSD) test at  $p < 0.05$ . Treatment means are presented as mean ± standard error (SE). Statistical summaries (ANOVA tables, mean squares and LSD groupings) are reported in the results.

### Quality control and reproducibility

All field operations, measurements and laboratory analyses followed standardised protocols. Instrument calibration, randomisation procedures and replication were implemented to reduce bias. Raw data and analysis scripts are archived and available upon reasonable request to ensure reproducibility. Field procedures and photographs of the experimental setup are provided in the Appendix.

## Results and Discussion

### Descriptive statistics and overall patterns

Measured growth and yield traits showed moderate variability across treatments. Plant height ranged from 217 to 258 cm (mean ± SD = 236.26 ± 9.71 cm), stem diameter from 14 to 23 mm (18.96 ± 2.11 mm), number of leaves per plant 12.2–15.2 (13.39 ± 0.69), cob length 14.0–19.1 cm (16.52 ± 1.26 cm), cob diameter 37–44.5 mm (39.98 ± 1.62), number of cobs per plant 1–2 (1.58 ± 0.29), number of cobs per plot 54–90 (69.38 ± 9.63), 100-seed weight 16–21 g (18.60 ± 1.21) and grain yield 1.93–7.63 t ha<sup>-1</sup> (5.50 ± 1.44). Coefficients of variation ranged from 7.12 to 20.55 %, indicating acceptable experimental precision and moderate variability among measured traits, confirming the reliability of the dataset.

### Analysis of variance and main effects of irrigation and mulch treatments

The split-plot ANOVA (Table 1–3) demonstrated that mulch type exerted a consistently significant effect on all measured growth and yield traits ( $p < 0.01$ ). In contrast, irrigation interval had a significant

**Table 1.** ANOVA for plant height, stem diameter and leaf number under irrigation and mulch treatments

| Source         | DF | Plant height |             | Stem diameter |             | Number of leaves plant <sup>-1</sup> |             |
|----------------|----|--------------|-------------|---------------|-------------|--------------------------------------|-------------|
|                |    | MS           | p           | MS            | p           | MS                                   | p           |
| Replication    | 2  | 204.91       | 0.0096 **   | 2.95          | 0.0214 *    | 0.668                                | < 0.0001 ** |
| Irrigation (I) | 2  | 52.22        | 0.0891 ns   | 0.765         | 0.1586 ns   | 0.013                                | 0.0651 ns   |
| Mulch (M)      | 3  | 768.34       | < 0.0001 ** | 36.78         | < 0.0001 ** | 3.663                                | < 0.0001 ** |
| I × M          | 6  | 7.18         | 0.9122 ns   | 0.792         | 0.8460 ns   | 0.331                                | 0.0488 *    |
| Error          | 22 | 21.76        | –           | 1.82          | –           | 0.124                                | –           |

DF: degrees of freedom; MS: mean square; p: probability value; ns: not significant; \* $p < 0.05$ ; \*\* $p < 0.01$ .

**Table 2.** ANOVA for maize cob traits under different irrigation and mulching treatments

| Source         | DF | Cob length |           | Cob diameter |             | Number of cobs plant <sup>-1</sup> |             |
|----------------|----|------------|-----------|--------------|-------------|------------------------------------|-------------|
|                |    | MS         | p         | MS           | p           | MS                                 | p           |
| Replication    | 2  | 8.73       | 0.0044 ** | 2.28         | 0.0673 ns   | 0.018                              | 0.8297 ns   |
| Irrigation (I) | 2  | 2.07       | 0.0537 ns | 2.53         | 0.0574 ns   | 0.038                              | 0.6895 ns   |
| Mulch (M)      | 3  | 6.81       | 0.0002 ** | 19.09        | < 0.0001 ** | 0.594                              | < 0.0001 ** |
| I × M          | 6  | 0.24       | 0.8601 ns | 0.35         | 0.9312 ns   | 0.015                              | 0.7842 ns   |
| Error          | 18 | 0.590      | –         | 1.180        | –           | 0.029                              | –           |

DF: degrees of freedom; MS: mean sum of squares; P: probability value; I: irrigation; M: mulch; I × M: interaction between irrigation and mulch; ns: non-significant; \* $p < 0.05$ ; \*\* $p < 0.01$ .

**Table 3.** ANOVA for maize yield traits under different irrigation and mulching treatments based on mean square

| Source         | DF | Number of cobs plot <sup>-1</sup> |             | 100-seed weight |           | Grain yield |           |
|----------------|----|-----------------------------------|-------------|-----------------|-----------|-------------|-----------|
|                |    | MS                                | p           | MS              | p         | MS          | p         |
| Replication    | 2  | 93.80                             | 0.3023 ns   | 1.23            | 0.2108 ns | 0.65        | 0.1533 ns |
| Irrigation (I) | 2  | 17.62                             | 0.7512 ns   | 3.08            | 0.0642 ns | 2.19        | 0.0260 *  |
| Mulch (M)      | 3  | 712.59                            | < 0.0001 ** | 7.62            | 0.0005 ** | 11.14       | 0.0009 ** |
| I × M          | 6  | 16.31                             | 0.7799 ns   | 0.60            | 0.6145 ns | 1.55        | 0.3462 ns |
| Error          | 18 | 30.89                             | –           | 0.79            | –         | 1.28        | –         |

DF: degrees of freedom; MS: mean sum of squares; P: probability value; I: irrigation; M: mulch; I × M: interaction between irrigation and mulch; ns: non-significant; \* $p < 0.05$ ; \*\* $p < 0.01$ .

influence only on grain yield ( $F(2, 4) = 10.40$ ,  $p = 0.026$ ), while its effects on vegetative and cob traits were not statistically significant. The irrigation × mulch interaction was not significant for grain yield or other measured traits ( $p > 0.05$ ), indicating that treatment effects were independent under the conditions of this study. Overall, mulch treatments had a stronger influence on crop performance than irrigation scheduling in this experiment, particularly for vegetative growth and yield components.

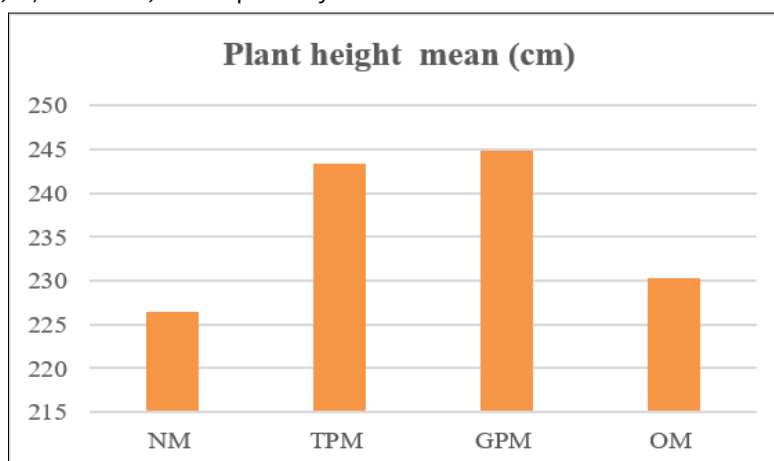
### Vegetative growth and yield components

The TPM and GPM significantly improved vegetative growth and yield components compared with OM and NM treatments (Fig. 2, Table 4). Plant height, stem diameter, cob length, cob diameter, number of cobs per plant, number of cobs per plot and 100-seed weight were consistently higher under TPM and GPM. Across treatments, the mean number of cobs per plant was  $1.58 \pm 0.29$ , reaching  $1.84 \pm 0.06$  under TPM and  $1.72 \pm 0.06$  under GPM. Similarly, 100-seed weight increased from an overall mean of  $18.60 \pm 0.12$  g to  $19.13 \pm 0.30$  g and  $19.62 \pm 0.30$  g under TPM and GPM, respectively. These responses may be associated with improved soil hydrothermal conditions under plastic mulch, including reduced soil evaporation, moderated soil temperature and improved early-season moisture availability, which collectively enhance crop establishment and biomass accumulation (19, 20). Similar positive effects of plastic mulching on maize growth and yield have been widely reported in previous studies under water-limited environments (15, 21, 22). In contrast, the comparatively lower

performance of organic mulch may be related to thinner and less uniform soil coverage, slower soil warming and gradual decomposition during the growing season (23–25). In addition, decomposition of straw residues with relatively high C : N ratios may temporarily immobilise available soil nitrogen through microbial activity, thereby reducing short-term nitrogen availability for crop growth. Similar limitations of organic mulches compared with plastic films have been reported in previous comparative studies (26, 27).

### Grain yield and irrigation effects

Mulch type significantly influenced grain yield and yield components (Table 4). The TPM and GPM produced higher numbers of cobs per plant ( $1.84 \pm 0.06$  and  $1.72 \pm 0.06$ , respectively) and greater 100-seed weight ( $19.13 \pm 0.30$  g and  $19.62 \pm 0.30$  g, respectively) compared with OM and NM treatments. Mean grain yield across treatments was  $5.50 \pm 1.44$  t ha<sup>-1</sup>, with TPM and GPM producing the highest yields ( $6.46 \pm 0.38$  t ha<sup>-1</sup>), whereas OM and NM resulted in lower yields ( $4.42$ – $4.66$  t ha<sup>-1</sup>) (Fig. 3). These represent yield increases of approximately 39–46 % under plastic mulch treatments. The higher grain yield observed under TPM and GPM may be associated with improved soil moisture conservation and reduced evaporative water loss during critical reproductive stages, which can enhance grain filling under limited irrigation conditions. Similar yield improvements under plastic mulching have been widely reported in previous studies conducted under water-limited environments (5, 20, 21).

**Fig. 2.** Mean plant height under four mulch treatments.

NM: no mulch; TPM: transparent plastic mulch; GPM: green plastic mulch; OM: organic maize straw. Bars show mean  $\pm$  SE.

**Table 4.** Subplot (mulch) means  $\pm$  SE and LSD groupings ( $\alpha = .05$ )

| Mulch                  | Plant height (cm) mean $\pm$ SE | Stem diameter (mm) Mean $\pm$ SE | Number of leaves mean $\pm$ SE |
|------------------------|---------------------------------|----------------------------------|--------------------------------|
| NM                     | 226.44 $\pm$ 1.55 b             | 16.57 $\pm$ 0.45 c               | 12.37 $\pm$ 0.12 c             |
| TPM                    | 243.44 $\pm$ 1.55 a             | 20.70 $\pm$ 0.45 a               | 13.67 $\pm$ 0.12 ab            |
| GPM                    | 244.81 $\pm$ 1.55 a             | 20.57 $\pm$ 0.45 a               | 14.12 $\pm$ 0.12 a             |
| OM                     | 230.33 $\pm$ 1.55 b             | 18.00 $\pm$ 0.45 b               | 13.17 $\pm$ 0.12 bc            |
| LSD ( $\alpha = .05$ ) | 4.62                            | 1.34                             | 0.35                           |
| CV %                   | 1.97                            | 7.12                             | 2.62                           |

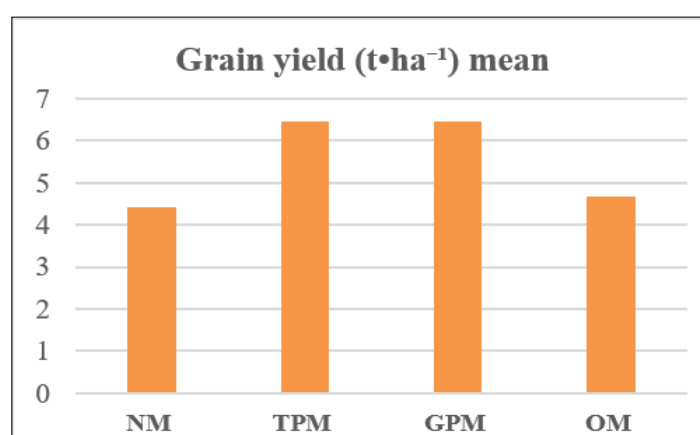
| Mulch                  | Cob length (cm) Mean $\pm$ SE | Cob diameter (mm) Mean $\pm$ SE | Number of cobs plant <sup>-1</sup> Mean $\pm$ SE |
|------------------------|-------------------------------|---------------------------------|--------------------------------------------------|
| NM                     | 15.39 $\pm$ 0.26 c            | 38.25 $\pm$ 0.36 b              | 1.26 $\pm$ 0.06 c                                |
| TPM                    | 17.24 $\pm$ 0.26 a            | 41.15 $\pm$ 0.36 a              | 1.84 $\pm$ 0.06 a                                |
| GPM                    | 17.17 $\pm$ 0.26 a            | 41.23 $\pm$ 0.36 a              | 1.72 $\pm$ 0.06 a                                |
| OM                     | 16.30 $\pm$ 0.26 b            | 39.30 $\pm$ 0.36 b              | 1.51 $\pm$ 0.06 b                                |
| LSD ( $\alpha = .05$ ) | 0.76                          | 1.08                            | 0.17                                             |
| CV %                   | 4.65                          | 2.72                            | 10.75                                            |

| Mulch                  | Number of cobs plot <sup>-1</sup> Mean $\pm$ SE | 100 seed weight (g) Mean $\pm$ SE | Grain yield (t·ha <sup>-1</sup> ) mean $\pm$ SE |
|------------------------|-------------------------------------------------|-----------------------------------|-------------------------------------------------|
| NM                     | 57.97 $\pm$ 1.85 c                              | 17.96 $\pm$ 0.30 b                | 4.42 $\pm$ 0.38 b                               |
| TPM                    | 77.36 $\pm$ 1.85 a                              | 19.13 $\pm$ 0.30 a                | 6.46 $\pm$ 0.38 a                               |
| GPM                    | 75.44 $\pm$ 1.85 a                              | 19.62 $\pm$ 0.30 a                | 6.46 $\pm$ 0.38 a                               |
| OM                     | 66.75 $\pm$ 1.85 b                              | 17.70 $\pm$ 0.30 b                | 4.66 $\pm$ 0.38 b                               |
| LSD ( $\alpha = .05$ ) | 5.50                                            | 0.88                              | 1.12                                            |
| CV %                   | 8.01                                            | 4.78                              | 20.55                                           |

NM: no mulch; TPM: transparent plastic mulch; GPM: green plastic mulch; OM: organic maize straw.

Error(b) MSE = 1.2784 for yield; Error(b) df = 18. Means within a column followed by the same letter do not differ significantly according to Fisher's LSD test.

**Fig. 3.** Mean grain yield (t ha<sup>-1</sup>) under four mulch treatments.

NM: no mulch; TPM: transparent plastic mulch; GPM: green plastic mulch; OM: organic maize straw. Bars show mean  $\pm$  SE.

### Main plot (irrigation) effects on grain yield

Irrigation interval significantly affected grain yield (Fig. 4, Table 5). The 7-day and 10-day irrigation intervals produced statistically similar yields (5.86 and 5.62 t ha<sup>-1</sup>, respectively), both significantly higher than the 14-day interval (5.03 t ha<sup>-1</sup>). These findings suggest that prolonged irrigation intervals may negatively affect reproductive processes such as pollination and grain filling, resulting in reduced grain yield under semi-arid conditions.

### Interaction and buffering by mulches

The irrigation  $\times$  mulch (I  $\times$  M) interaction was not statistically significant for grain yield (Table 3). However, TPM and GPM maintained numerically higher yields under the 14-day irrigation

interval compared with OM and NM treatments. This pattern suggests a possible buffering effect of plastic mulch under extended irrigation intervals, likely associated with improved soil moisture conservation and moderated soil temperature. Nevertheless, because the interaction effect was not statistically significant, these responses should be interpreted as numerical trends rather than confirmed interaction effects. Similar findings have been reported in previous studies where plastic mulching consistently improved maize productivity, while mulch  $\times$  irrigation interactions remained non-significant due to environmental variability and field heterogeneity under field conditions (10, 19).

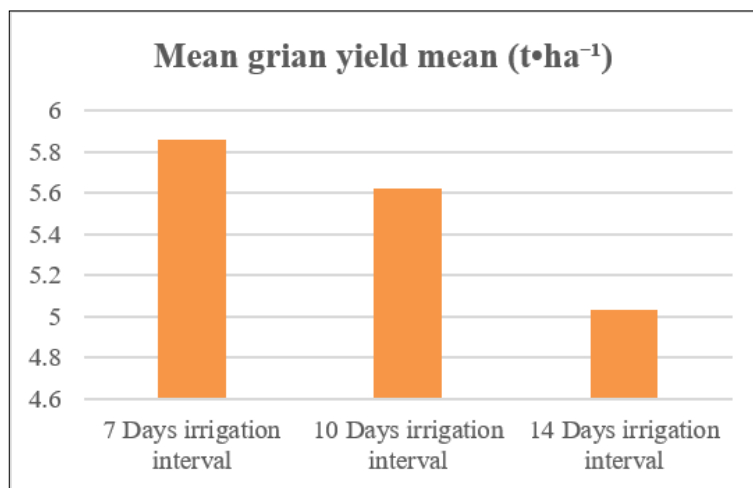
### Mechanistic interpretation

The observed improvements in vegetative growth, yield components and grain yield under plastic mulch treatments are likely associated with improved soil microclimatic conditions. Plastic mulches can reduce non-productive soil evaporation, conserve near-surface soil moisture, moderate soil temperature fluctuations and suppress weed competition, thereby improving water availability during critical early growth stages. These conditions may enhance root development, nutrient uptake and assimilate partitioning toward reproductive organs during grain filling, ultimately contributing to improved cob development and grain yield.

**Table 5.** Irrigation interval means for grain yield (t ha<sup>-1</sup>)  $\pm$  SE, (n = 12)

| Irrigation interval (days)  | Mean (t ha <sup>-1</sup> ) $\pm$ SE |
|-----------------------------|-------------------------------------|
| 7 days irrigation interval  | 5.86 $\pm$ 0.13 a                   |
| 10 days irrigation interval | 5.62 $\pm$ 0.13 a                   |
| 14 days irrigation interval | 5.03 $\pm$ 0.13 b                   |
| LSD ( $\alpha = 0.05$ )     | 0.52                                |
| CV %                        | 8.33                                |

Means within a column followed by the same letter do not differ significantly according to Fisher's LSD test.



**Fig. 4.** Main plot irrigation interval effects on grain yield (7, 10 and 14 days) with mean  $\pm$  SE.

Previous studies conducted under semi-arid environments similarly reported that plastic film mulching improves maize growth and productivity through enhanced soil hydrothermal conditions and reduced evaporative water losses (5, 10, 19, 22). Several authors further noted that the benefits of plastic mulching become more pronounced under limited irrigation conditions, where evaporation represents a major pathway of water loss. Under such environments, mulch primarily functions by conserving soil moisture and stabilising root-zone conditions rather than directly altering crop physiological responses to irrigation timing (28). The present findings are generally consistent with these reports, as TPM and GPM treatments maintained superior vegetative growth and grain yield across irrigation intervals. However, because continuous measurements of soil moisture, soil temperature, evapotranspiration and crop water use were not conducted in this study, these mechanisms remain inferential rather than directly demonstrated. Therefore, future research incorporating continuous soil monitoring, plot-level water balance measurements and multi-season validation is necessary to confirm the physiological and hydrological mechanisms underlying mulch performance under high-altitude semi-arid conditions.

#### Practical implications

In high-altitude semi-arid systems similar to Ghudar, the use of plastic mulches (TPM and GPM) may improve maize productivity and help stabilise yield under limited or irregular irrigation conditions. Under the conditions of this study, combining plastic mulching with a 7–10 day irrigation interval resulted in higher grain yield compared with longer irrigation intervals. However, these findings should be validated through multi-season and location-specific trials before large-scale recommendation. In addition, adoption of plastic mulching should consider economic feasibility, residue disposal and potential environmental risks such as microplastic accumulation. Biodegradable mulches and improved residue management practices may provide more sustainable alternatives for future application (9, 24).

#### Limitations and future research

This study was limited by its single-season design, lack of continuous measurements of soil moisture and temperature and the use of irrigation interval rather than precise volumetric water application at the plot level. These limitations may have restricted a full understanding of crop–water interactions under the tested conditions. Future research should focus on multi-season and multi-

location field experiments, continuous soil monitoring using sensors and irrigation scheduling based on applied water volume. In addition, economic evaluation, assessment of water productivity and testing of biodegradable mulch materials should be considered to improve sustainability and practical applicability. Reporting standardised effect sizes (e.g., percent change relative to control and partial  $\eta^2$ ) and confidence intervals would further strengthen the robustness and comparability of future studies.

#### Synthesis

Overall, the findings of this single-season field experiment indicate that mulch type played a major role in determining maize performance under high-altitude semi-arid conditions. Plastic mulches (TPM and GPM) consistently improved vegetative growth, yield components and grain yield compared with organic mulch and no-mulch treatments. Irrigation interval also affected grain yield, with shorter intervals (7–10 days) generally resulting in higher yields than the 14-day interval. However, the absence of a significant interaction between irrigation and mulch suggests that their effects were largely independent under the conditions of this study. These results suggest that plastic mulching, combined with moderately frequent irrigation, may be a useful strategy for improving maize productivity of the local cultivar Logari in similar environments, although confirmation through multi-season and sustainability-focused studies is required.

#### Conclusion

In this high-altitude, semi-arid single-season field study, plastic mulching (transparent and green films) was associated with higher maize grain yield compared with organic straw mulch and bare soil, with an approximate 40 % increase under the tested conditions. The combination of plastic mulching and a 7–10 day irrigation interval appeared to improve yield performance; however, these findings should be interpreted cautiously due to the single-season nature of the experiment and the lack of continuous soil monitoring. Beyond the local context, the results suggest that plastic mulching may offer a promising strategy for improving maize productivity in similar water-limited environments. However, concerns regarding long-term environmental sustainability remain important. Future research should focus on multi-season validation, soil moisture and temperature monitoring and evaluation of biodegradable mulch alternatives alongside economic feasibility analyses to support sustainable adoption.

## Acknowledgements

The authors thank Daykundi University and Daykundi Agriculture Institute for providing facilities. Special appreciation goes to Esmail Omid and Mowladad for their assistance in farm preparation and irrigation, along with colleagues who offered technical and general support.

## Authors' contributions

YK conceived and designed the study, led the field experiment, coordinated farm work, collected data, performed statistical analysis and drafted the manuscript. MHA actively participated in all stages of the research particularly in farm operations and data collection and contributed to data analysis and manuscript revision. MSM provided methodological guidance and advised on the study design. NN and HP offered consultation, assisted with data interpretation and supported manuscript review. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

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