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***Full Length Article***

# Tillage and Mulching for Improved Water Use Efficiency and Maize Yield in Punjab, Pakistan

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## Abstract

Maize productivity in semi-arid regions is hindered by soil compaction, reduced fertility, and inefficient resource management. These factors result in limited water infiltration and root growth, reduced organic matter and enhanced erosion, and excessive fertilizer use and inadequate irrigation scheduling. To address these challenges, field experiments were conducted at the Agronomic Research Area, University of Agriculture Faisalabad, Pakistan. The study evaluated the effects of four tillage methods (zero tillage; cultivator twice + planking; moldboard plough + cultivator twice + planking; chisel plough + cultivator twice + planking) and three mulching treatments (no mulching; plastic mulch; sorghum straw mulch at 5 t/ha), on maize performance. The results showed that chisel ploughing increased plant height by 14.1%, cob length by 12.5%, grains per cob by 21.5%, and grain yield by 24.5% compared to zero tillage. Sorghum straw mulch also improved plant height by 10.3%, cob length by 9.1%, and grains per cob by 15.6% compared to no mulching. Water use efficiency (WUE) significantly improved by 27% and 33% in 2017 and 2018, respectively with chisel ploughing and sorghum straw mulch. The combination of chisel ploughing and sorghum straw mulch achieved the highest economic returns, with a net income of Rs. 89853/ha and a benefit-cost ratio of 1.82, which was 64% higher than the lowest BCR recorded with zero tillage and plastic mulching. In conclusion, chisel plough + cultivator twice + planking and sorghum straw mulching are effective practices for enhancing maize yield, WUE, and economic viability in semi-arid regions. These findings have important implications for sustainable maize production and resource management in water-scarce areas.

**Keywords:** Crop productivity; Agronomic practices; Semi-arid regions; Economic viability; Resource management, Maize

## Introduction

Over the past several decades, global warming has intensified, leading to increasingly unfavorable conditions for farming (Rizwanullah *et al*. 2023). Pakistan ranks as the fifth most vulnerable country to climate change (Ahmad *et al*. 2015). With a growing population and rapid urbanization, the adverse effects of climate change are expected to be severe (Anwar *et al*. 2020). The country is particularly susceptible to climate-related challenges and has been listed as the 12$^{th}$ most severely affected nation due to its impact on agriculture and livelihoods (Awan and Yaseen 2017).

Global warming has intensified over the last several decades, leading to increasingly less favorable conditions for agriculture (Rizwanullah *et al*. 2023). Pakistan ranks fifth globally in terms of climate vulnerability (Ahmad *et al*. 2015). The compounding effects of rapid urbanization and population growth are expected to exacerbate the adverse impacts of climate change (Anwar *et al*. 2020). Notably, Pakistan has been identified as the 12$^{th}$ most climate-affected nation worldwide, with significant implications for agricultural productivity and livelihood security (Awan and Yaseen 2017).

Maize (*Zea mays* L.) productivity is influenced by multiple factors, including integrated pest management (IPM) strategies, irrigation scheduling and climatic variability (Rosner *et al*. 2008). Tillage is an essential agronomic practice that modifies soil physical attributes, enhancing overall soil quality and fertility (Khan *et al*. 2010). By optimizing soil structure and aeration, tillage improves nutrient use efficiency, increases nutrient availability, ultimately contributing to enhance crop productivity (Bahadar *et al*. 2007). Furthermore, tillage plays a crucial role in regulating soil organic matter dynamics (Tian *et al.* 2016), as it enhances soil aeration, accelerates the decomposition of crop residues, and

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increases nitrogen availability for plant uptake, thereby promoting soil fertility and plant growth (Dinnes *et al*. 2002). Deep tillage, extending to a depth of 30 cm, has been shown to be highly effective in fracturing hardpan layers in subsoil (Hou *et al.* 2012). Furthermore, deep ploughing enhances soil structure by reducing soil bulk density and increasing porosity, which in turn facilitates root growth, improves water infiltration rates, and boosts nutrient availability. This ultimately leads to superior crop yields compared to zero-tillage systems (Ramadhan 2021).

Optimized tillage and mulching strategies are important in maintaining soil health and promoting sustainable agricultural productivity. Furthermore, Mulching, a significant conservation practice, entails covering the soil surface to create a favorable microclimate that fosters optimal growth conditions, enhances crop water use efficiency, and maximizes crop production efficiency (Jabran *et al*. 2015; Thakur and Kumar 2021).

Mulching has been widely recognized for its beneficial effects on soil hydrothermal regimes, particularly in enhancing soil water retention and mitigating soil temperature fluctuations, thereby creating a favorable environment for maize growth. Additionally, mulching has been shown to reduce nitrate leaching and improve WUE (Dai *et al.* 2021). In arid and semi-arid regions, mulching plays a vital role in managing water scarcity by conserving soil moisture and reducing evapotranspiration (Zhu *et al*. 2021; Li *et al*. 2023a). By optimizing water and nutrient uptake, mulching promotes healthier plant development, enhances resilience to environmental stresses (Wen *et al*. 2023). Mulching has emerged as a widely adopted practice among gardeners, owing to its efficacy in mitigating water loss through evaporation and preventing soil erosion (Kishore *et al*. 2022). Furthermore, plastic mulch serves as a photonic barrier, effectively inhibiting weed growth by suppressing photosynthetic activity (Amare and Desta 2021). As a crucial component of cropping systems, mulches significantly enhance soil fertility and crop performance by conserving moisture, suppressing weeds, improving soil consistency, and moderating soil temperature, thereby protecting roots from thermal damage. The cumulative effect of these benefits undoubtedly leads to enhanced crop yield (Zamir *et al*. 2013; Minhas *et al*. 2023).

Straw mulching has been shown to enhance soil water use efficiency, leading to increased grain yield. Notably, sorghum straw mulch has demonstrated superior efficacy in maintaining soil moisture and moderating soil temperature, thereby creating a favorable environment for root development and yield improvement (Ramadhan 2021). Moreover, the integration of various tillage operations with mulch practices is crucial for optimizing soil chemical and physical properties, as well as promoting soil microbial activity, which are essential prerequisites for enhanced crop production (Reddy *et al*. 2002). Tillage practices are a critical component of sustainable crop production systems, yet the optimal integration of tillage and mulching strategies to maximize maize yields remains unclear. To bridge this knowledge gap, our study undertakes a comprehensive evaluation of various tillage methods and mulching practices to identify the most effective combination for sustainable maize production.

## Materials and Methods

### Experimental location

This experimentation was carried out at the Agronomic Research Farm, Department of Agronomy, University of Agriculture, Faisalabad, Punjab, Pakistan for two cropping seasons during 2017 and 2018. Experimentation was aimed at investigating the impact of various tillage practices and mulching treatments on maize crop productivity. The site of experiment was located at 31.3° North latitude, 73.05° East longitude and 184 m elevation. In soil analysis, soil of the site was identified as Hafizabad series (fine-loamy, mixed, hyperthermic, Typic Calciargids) with a sandy clay loam texture. The soil analysis report prior to experimentation is presented in Table 1.

### Crop management and experimental design

Experiment was laid out with three replicates under randomized complete block design (RCBD) with split-plot pattern. Tillage practices were kept as main factor in main plots and mulching treatments in sub plots with a net plot size of 6 m × 4.5 m. Maize hybrid DK-6714 of Monsanto was planted with seed rate of 25 kg ha$^{-1}$. Crop was sown on 15$^{th}$ and 17$^{th}$ July in 2017 and 2018 respectively in fallow field. Row spacing was maintained 75 cm and plant × plant distance was kept 25 cm. The experimental treatments comprised of four tillage interventions (zero tillage (control); cultivator twice + planking once; Moldboard plough 1 time + 2 times cultivator + planking once; 1 time chisel plough + 2 times cultivator + planking once) and three mulching treatments (no mulching (control); plastic mulch; straw mulch (sorghum) at 5 tones ha$^{-1}$) were used. Strips of polythene mulch (transparent plastic 300 cm wide; 8 $\mu$m thick) were cut to the appropriate length and breadth, put between the plant rows, and then topped with soil around the edges to hold it firmly. Sorghum stalks (Sorghum-2011) at physiological maturity were procured from a farmer field near research area and chopped into mulch by electric chopper and were spread in rows. Recommended dose of nitrogen, phosphorus and potassium fertilizers were applied at of 230:145:95 kg/ha (recommended by Punjab Agriculture Department) using urea, di-ammonium phosphate (DAP) and sulfate of potash (SOP) as source. To attain the best potential growth, three splits of nitrogen were applied: one third at seeding, one third at the five-leaf stage (32 DAS) and one third at tasseling (55 DAS). The whole amount of potash and phosphorus was spread as a basal dose prior to sowing.

**Table 1:** Soil analysis report of experimental area

| Characteristics | Results |
|---|---|
| Texture | Sandy clay |
| pH | 8.05 |
| Electrical Conductivity (EC) | 0.36 dS $m^{-1}$ |
| Nitrogen | 0.019% |
| Available phosphorus (AP) | 7.8 mg. $kg^{-1}$ |
| Exchangeable potassium (EK) | 118 mg. $kg^{-1}$ |
| Soil organic matter (SOM) | 0.47% |

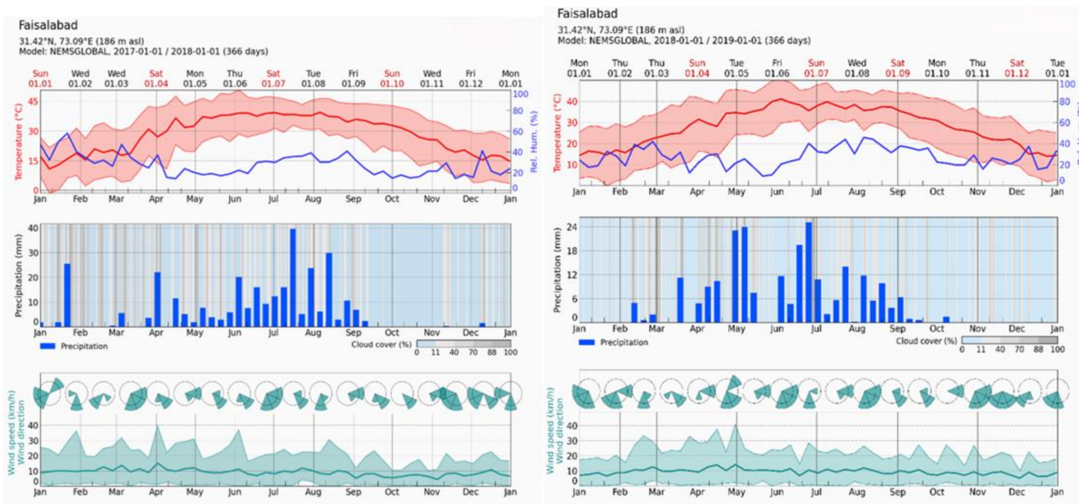


**Fig. 1:** Relative humidity, mean temperature, rainfall, wind speed and direction during 2017 (**a**) and 2018 (**b**)

After sowing, the first irrigation was applied at sowing time, then crop received five subsequent irrigations of 7.5 cm each, measured by cutthroat flume, as required at various plant growth stages till physiological maturity of the crop. Ground and canal water were used for irrigation as per availability and crop requirement.

### Crop growth, harvest and yield traits

The maize crop was manually harvested on November 10 and 15 in 2017 and 2018, respectively and left in the plots for one week for natural sun drying to ensure optimal quality. At maturity, the number of plants was counted manually from each plot to calculate plant population per square meter. The height of five randomly selected plants was measured with a meter rod and the average height was calculated. Additionally, the total number of cobs attached to these five plants was counted and averaged. Five representative cobs were collected from each plot, and their lengths were measured and averaged using a scale. The number of grain rows per cob was recorded from five randomly selected plants in each treatment and averaged. The grains per cob were counted for each cob from the same five plants, and the average was determined. A grain counter was used to count 1000 grains from each plot's seed lot, which were weighed using an electronic balance. Grain yield was calculated in tons per hectare after bulking the threshed, cleaned, air-dried maize grains, ensuring moisture content was reduced to 14%. Biological yield was assessed by weighing dried crop bundles with a spring balance. After removing cobs and leaves, the dried stalks were weighed to calculate average stalk yield (t $ha^{-1}$). The harvest index was determined as a percentage by taking the ratio of economic yield to biological yield for each experimental unit. Grain protein was measured using Near-Infrared Reflectance Spectroscopy (NIRS) that uses infrared light to measure the protein content of maize grains and Soxhlet extraction method was used to know the oil content of maize as adopted by Alamu *et al*. (2022). Weather data presented in Fig. 1a-b was taken from the meteorology station of Agronomy Department, University of Agriculture, Faisalabad, Punjab, Pakistan.

### Total water inputs and water use efficiency

Total water input was quantified using the method described by Buland *et al*. (1994) and detailed in Ishfaq *et al.* (2020). The total water consumption during the crop growth period was measured by installing a cut-throat flume in the main water channel. The total water depth was estimated using the formula DA=QT. Where “D” is the irrigation water depth (mm), “A” represents the area of experimental unit to

**Table 2:** The effects of tillage and mulching practices on maize agronomic characteristics and yield parameters

| Treatment | No. of cobs/plant | | Cob length (cm) | | Grain rows/cob | | Grains/cob | | 1000-grain weight (g) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| $T_1$ | 1.5 | 1.5 | 14.5$^d$ | 17.5$^d$ | 14.8$^b$ | 15.0$^d$ | 396.6$^c$ | 419.6$^d$ | 248.2$^c$ | 252.8$^c$ |
| $T_2$ | 1.4 | 1.4 | 15.4$^c$ | 18.9$^c$ | 15.1$^b$ | 15.7$^c$ | 456.1$^{bc}$ | 482.6$^c$ | 257.8$^{bc}$ | 262.0$^{bc}$ |
| $T_3$ | 1.4 | 1.5 | 16.8$^b$ | 20.5$^b$ | 15.8$^{ab}$ | 16.4$^b$ | 507.9$^b$ | 549.4$^b$ | 263.6$^{ab}$ | 270.3$^{ab}$ |
| $T_4$ | 1.5 | 1.5 | 18.8$^a$ | 21.8$^a$ | 16.8$^a$ | 17.1$^a$ | 584.4$^a$ | 612.9$^a$ | 272.6$^a$ | 278.9$^a$ |
| *HSD ($P \leq 0.05$)* | *NS* | *NS* | *0.30* | *1.05* | *1.39* | *0.40* | *66.95* | *54.45* | *9.75* | *11.97* |
| $M_1$ | 1.4 | 1.4 | 15.9$^b$ | 19.2$^b$ | 15.4$^{ab}$ | 15.8$^b$ | 456.5$^b$ | 495.7$^b$ | 256.1$^b$ | 263.1$^b$ |
| $M_2$ | 1.4 | 1.5 | 16.1$^b$ | 19.7$^{ab}$ | 15.6$^b$ | 16.0$^{ab}$ | 488.1$^{ab}$ | 516.6$^{ab}$ | 260.9$^{ab}$ | 265.9$^{ab}$ |
| $M_3$ | 1.5 | 1.5 | 17.0$^a$ | 20.1$^a$ | 15.8$^a$ | 16.3$^a$ | 514.2$^a$ | 536.1$^a$ | 264.6$^a$ | 268.9$^a$ |
| *HSD ($P \leq 0.05$)* | *NS* | *NS* | *0.26* | *0.49* | *0.39* | *0.32* | *54.04* | *35.41* | *7.55* | *5.07* |

$T_1$: Zero Tillage, $T_2$: Cultivator + Planking, $T_3$: MB Plough + cultivator + planking, $T_4$: Chisel plough + cultivator + planking, $M_1$: No mulching, $M_2$: Polythene mulch and $M_3$: Sorghum straw mulch, HSD: honestly significant difference; values sharing different lettering for a parameter are different significantly ($P \leq 0.05$) by the Tukey's HSD test; NS = Not significant at ($P \leq 0.05$)

**Table 3:** The effects of tillage and mulching practices on maize yield and water use efficiency

| Treatment | Stalk Yield (t ha$^{-1}$) | | Biological Yield (t ha$^{-1}$) | | Harvest Index (%) | | Water Input (mm) | | WUE (kg/ha/mm) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| Tillage system (T) | | | | | | | | | | |
| $T_1$ | 9.2$^c$ | 9.9$^d$ | 13.2$^c$ | 14.7$^d$ | 36.7 | 35.8 | 579.3$^b$ | 579.7$^b$ | 10.9$^b$ | 12.3$^b$ |
| $T_2$ | 10.1$^{bc}$ | 10.9$^c$ | 15.7$^b$ | 16.5$^c$ | 35.4 | 36.5 | 586.8$^{ab}$ | 584.8$^{ab}$ | 12.4$^{ab}$ | 13.9$^{ab}$ |
| $T_3$ | 10.9$^b$ | 11.7$^b$ | 17.1$^{ab}$ | 17.9$^b$ | 37.6 | 37.8 | 590.4$^a$ | 588.0$^{ab}$ | 13.7$^{ab}$ | 14.8$^{ab}$ |
| $T_4$ | 12.1$^a$ | 12.7$^a$ | 19.2$^a$ | 19.9$^a$ | 36.7 | 37.1 | 594.6$^a$ | 595.2$^a$ | 14.4$^a$ | 16.0$^a$ |
| *HSD ($P \leq 0.05$)* | *1.02* | *0.79* | *2.23* | *1.30* | *NS* | *NS* | *8.22* | *12.75* | *2.84* | *3.22* |
| Mulching practices (M) | | | | | | | | | | |
| $M_1$ | 10.1$^b$ | 11.0$^b$ | 15.5$^b$ | 16.6$^b$ | 36.9 | 36.9 | 583.3$^b$ | 579.5$^b$ | 11.9$^b$ | 12.8$^b$ |
| $M_2$ | 10.6$^{ab}$ | 11.3$^{ab}$ | 16.3$^{ab}$ | 17.2$^{ab}$ | 36.3 | 36.7 | 585.3$^b$ | 582.1$^b$ | 12.9$^{ab}$ | 14.8$^a$ |
| $M_3$ | 11.0$^a$ | 11.6$^a$ | 17.1$^a$ | 17.8$^a$ | 36.6 | 36.9 | 594.8$^a$ | 599.2$^a$ | 13.8$^a$ | 15.2$^a$ |
| *HSD ($P \leq 0.05$)* | *0.72* | *0.55* | *1.17* | *1.11* | *NS* | *NS* | *6.24* | *7.77* | *1.33* | *1.28* |

$T_1$: Zero Tillage, $T_2$: Cultivator + Planking, $T_3$: MB Plough + cultivator + planking, $T_4$: Chisel plough + cultivator + planking, $M_1$: No mulching, $M_2$: Polythene mulch and $M_3$: Sorghum straw mulch, HSD: honestly significant difference; values sharing different lettering for a parameter are different significantly ($P \leq 0.05$) by the Tukey's HSD test; NS=Not significant at ($P \leq 0.05$)

be irrigated, "Q" is water discharge ($ft^3s^{-1}$), and "T" shows the time of water input. Whereas WUE, in kg ha$^{-1}$ mm$^{-1}$, was calculated following the formula of Molden *et al.* (2007) given below:

$$\text{WUE} = \frac{\text{Grain yield}}{\text{Water (I + R)used}} \qquad (1)$$

### Economic analysis

The economic analysis was performed following the guidelines of CIMMYT International Maize and Wheat Improvement Center (1998). Fixed costs involved seed price, irrigation, fertilizer price, crop protection and harvesting and management charges. Variable costs comprised, tillage and mulching costs. Total income was generated from straw and grain market value. Net returns were calculated by subtracting total expenditure from total income. The benefit-cost ratio (BCR) was determined by dividing total income by total expenditure.

### Statistical analysis

The data regarding all dependent variables were analyzed by using Statistix 10 computer software (student version) while, Fisher's analysis technique was applied for analysis of variance (ANOVA) and treatment means were compared using Tukey (HSD) test at $P \leq 0.05$ (Steel *et al.* 1997). Data visualization was performed by using sigma plot software.

## Results

### Experimental weather indices

The climate conditions during the summer seasons of 2017 and 2018 differed in terms of temperature and rainfall. The mean minimum temperature was lower in 2017 (16°C) compared to 2018 (17.8°C), whereas the mean maximum temperature was higher in 2017 (39.5°C) than in 2018 (38.8°C). Rainfall patterns also varied between the two years. Total rainfall during the crop season was higher in 2018 (286 mm) than in 2017 (260 mm). However, the number of rainy days during crop growth was higher in 2017 (24 days) than in 2018 (19 days). Notably, September 2017 received more rainfall than September 2018, while October 2018 received more rainfall than October 2017, coinciding with the grain filling period. These differences in temperature and rainfall patterns between the two years may have impacted the growth and development of the maize crop (Fig. 2a-b).

### Growth

Plant height, an important trait for reducing weed

**Table 4:** Impact of various tillage systems and mulching practices on net income and Benefit Cost Ratio (BCR) of maize during 2017 and 2018

| Treatments | $T_1M_1$ | $T_1M_2$ | $T_1M_3$ | $T_2M_1$ | $T_2M_2$ | $T_2M_3$ | $T_3M_1$ | $T_3M_2$ | $T_3M_3$ | $T_4M_1$ | $T_4M_2$ | $T_4M_3$ | Units |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grain yield | 4.73 | 5.09 | 5.33 | 5.46 | 5.63 | 6.17 | 6.44 | 6.56 | 6.73 | 6.99 | 7.19 | 7.40 | t ha$^{-1}$ |
| Adj. G.Y. | 4.26 | 4.58 | 4.80 | 4.91 | 5.07 | 5.55 | 5.80 | 5.90 | 6.05 | 6.29 | 6.47 | 6.66 | 10% less |
| Value (US$) | 868 | 934 | 979 | 1002 | 1034 | 1133 | 1182 | 1203 | 1235 | 1282 | 1320 | 1358 | US$ 8/40 kg |
| Stalk yield | 18.22 | 19.01 | 20.01 | 20.62 | 21.12 | 21.35 | 21.9 | 22.73 | 23.32 | 23.72 | 24.87 | 25.66 | t ha$^{-1}$ |
| Adj. S.Y. | 16.40 | 17.11 | 18.01 | 18.56 | 19.01 | 19.22 | 19.71 | 20.46 | 20.99 | 21.35 | 22.38 | 23.09 | 10% less |
| Value (US$) | 171 | 178 | 187 | 193 | 198 | 200 | 205 | 213 | 218 | 222 | 233 | 240 | US$ 10.4/t |
| Gross income (US$) | 1039 | 1112 | 1166 | 1195 | 1231 | 1333 | 1387 | 1416 | 1453 | 1504 | 1553 | 1598 | US$ ha$^{-1}$ |
| Plough cost (US$) | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | US$ 31.6 ha$^{-1}$ |
| Plank cost (US$) | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | US$ 7.9 ha$^{-1}$ |
| Sowing cost (US$) | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | US$ 9.9 ha$^{-1}$ |
| Bund making cost (US$) | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | US$ 4 ha$^{-1}$ |
| Seed cost (US$) | 125 | 125 | 125 | 125 | 125 | 125 | 125 | 125 | 125 | 125 | 125 | 125 | US$ 125.5 ha$^{-1}$ |
| Fertilizer cost (US$) | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | 338 | US$ 338.3 ha$^{-1}$ |
| Irrigation cost (US$) | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | US$ 130.4 ha$^{-1}$ |
| Plant protection (US$) | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | US$ 26.7 ha$^{-1}$ |
| Harvesting cost (US$) | 59 | 59 | 59 | 59 | 59 | 59 | 59 | 59 | 59 | 59 | 59 | 59 | US$ 59.2 ha$^{-1}$ |
| Management cost (US$) | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | US$ 13.8 ha$^{-1}$ |
| Total (a) (US$) | 747 | 747 | 747 | 747 | 747 | 747 | 747 | 747 | 747 | 747 | 747 | 747 | Fixed Cost (US$ ha$^{-1}$) |
| Tillage cost (US$) | 0 | 0 | 0 | 40 | 40 | 40 | 89 | 89 | 89 | 83 | 83 | 83 | US$ ha$^{-1}$ |
| Mulching cost (US$) | 0 | 251 | 49 | 0 | 251 | 49 | 0 | 251 | 49 | 0 | 251 | 49 | US$ ha$^{-1}$ |
| Total (b) (US$) | 0 | 251 | 49 | 40 | 291 | 88 | 89 | 340 | 138 | 83 | 334 | 132 | Variable Cost (US$ ha$^{-1}$) |
| Total (a + b) (US$) | 747 | 998 | 796 | 787 | 1038 | 836 | 836 | 1087 | 885 | 830 | 1081 | 879 | Total Cost (US$ ha$^{-1}$) |
| Net income (US$) | 292 | 113 | 370 | 408 | 193 | 497 | 551 | 329 | 568 | 674 | 471 | 719 | (US$ ha$^{-1}$) |
| BCR | 1.39 | 1.11 | 1.46 | 1.52 | 1.19 | 1.59 | 1.66 | 1.30 | 1.64 | 1.81 | 1.44 | 1.82 | |

BCR: Benefit cost ratio, Adj. G.Y: Adjusted grain yield, Adj. S.Y: Adjusted stalk yield, US$: US dollars, $T_1$: Zero Tillage, $T_2$: Cultivator + Planking, $T_3$: MB Plough + cultivator + planking, $T_4$: Chisel plough + cultivator + planking, $M_1$: No mulching, $M_2$: Polythene mulch and $M_3$: Sorghum straw mulch, US$: US dollars

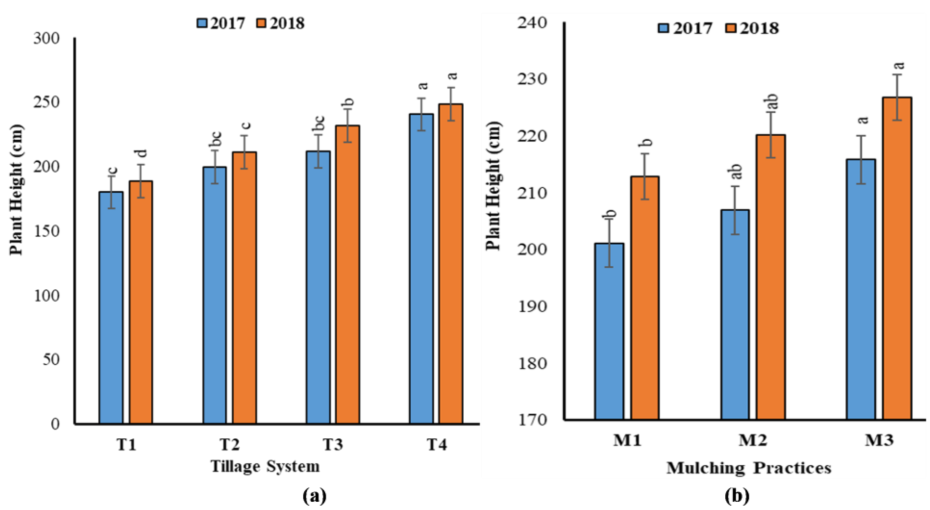


**Fig. 2:** The effects of tillage system (**a**) and mulching practices (**b**) on maize plant height (cm)
T1: Zero Tillage, T2: Cultivator + Planking, T3: MB Plough + cultivator + planking, T4: Chisel plough + cultivator + planking, M1: No mulching, M2: Polythene mulch and M3: Sorghum straw mulch, Bars (treatment mean ± standard error, n = 3) sharing different lettering for a parameter above the bar are different significantly ($P \leq 0.05$) by the Tukey's HSD test within same year

competition, was significantly affected by tillage practices. Chisel plough + cultivator + planking resulted in the tallest plants, with a height of 241 cm and 248 cm in 2017 and 2018, respectively. This was 33% and 31% taller than plants under zero tillage (180 cm and 189 cm in 2017 and 2018, respectively). Straw mulch also led to significantly taller plants, with a height of 216 cm and 227 cm in 2017 and 2018, respectively which was 7% and 6% taller than the control treatment (201 cm and 213 cm in 2017 and 2018, respectively). In contrast, the number of cobs per plant was not significantly affected by tillage practices and mulching treatments. The number of cobs per plant ranged from 1.3 to 1.5 in 2017 and from 1.3 to 1.6 in 2018. Notably, the interactive

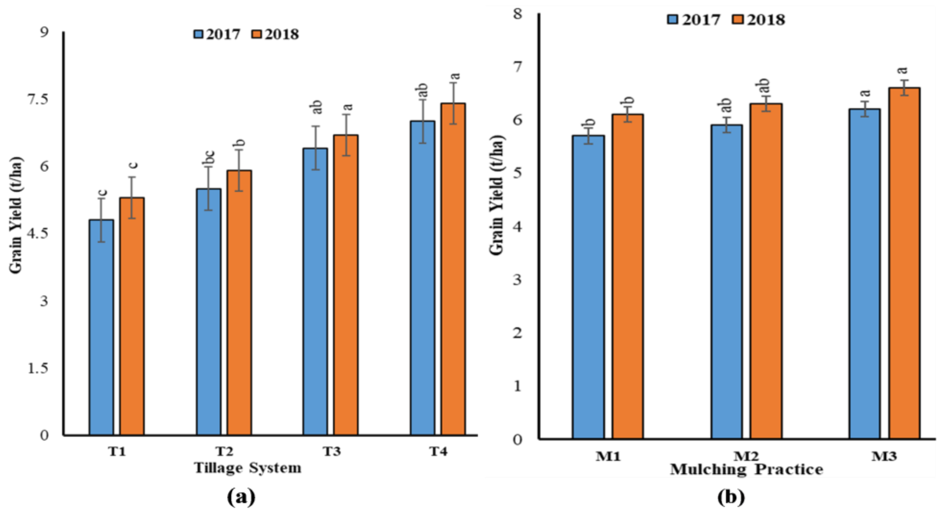


**Fig. 3:** The effects of tillage (**a**) and mulching practices (**b**) on maize grain yield (t/ha)
T1: Zero Tillage, T2: Cultivator + Planking, T3: MB Plough + cultivator + planking, T4: Chisel plough + cultivator + planking, M1: No mulching, M2: Polythene mulch and M3: Sorghum straw mulch, Bars (treatment mean ± standard error, n = 3) sharing different lettering for a parameter above the bar are different significantly ($P \leq 0.05$) by the Tukey's HSD test within same year

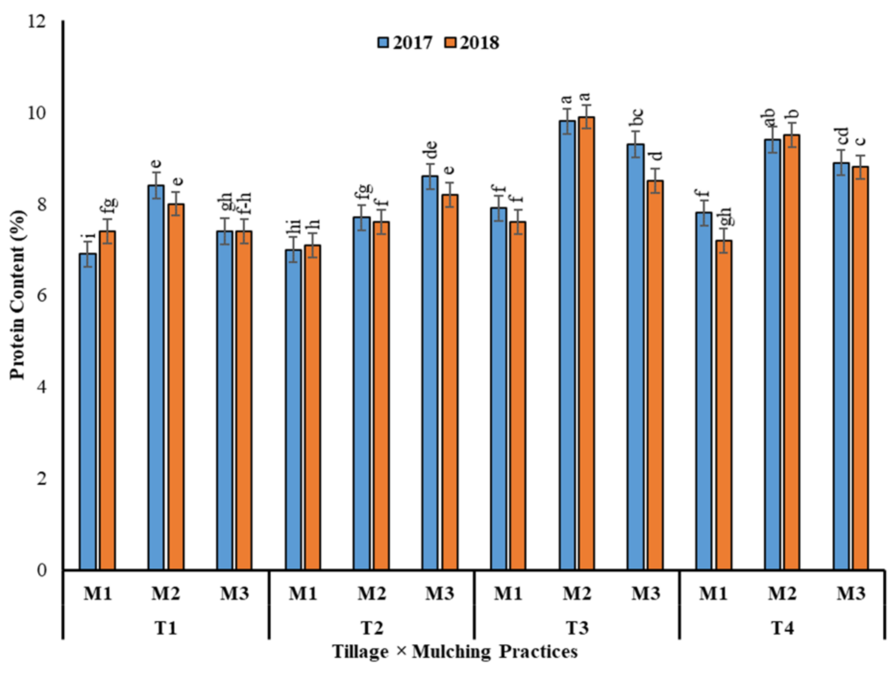


**Fig. 4:** The effects of tillage × mulching practices on maize protein content (%)
T1: Zero Tillage, T2: Cultivator + Planking, T3: MB Plough + cultivator + planking, T4: Chisel plough + cultivator + planking, M1: No mulching, M2: Polythene mulch and M3: Sorghum straw mulch, Bars (treatment mean ± standard error, n = 3) sharing different lettering for a parameter above the bar are different significantly ($P \leq 0.05$) by the Tukey's HSD test within same year

effect of tillage and mulching did not influence plant height or number of cobs per plant in either year, indicating that the main effects of tillage and mulching were additive (Table 2; Fig. 2a-b).

## Yield and yield components

Tillage and mulching practices significantly influenced maize yield and yield components (cob length, grain rows per cob, grains per cob, and 1000-grain weight, grain yield, stalk yield and biological yield). The main effects of tillage and mulching were additive, affecting all these parameters. However, the interactive effect of tillage and mulching treatments did not significantly influence any of these parameters (Table 2-3; Fig. 3a-b).

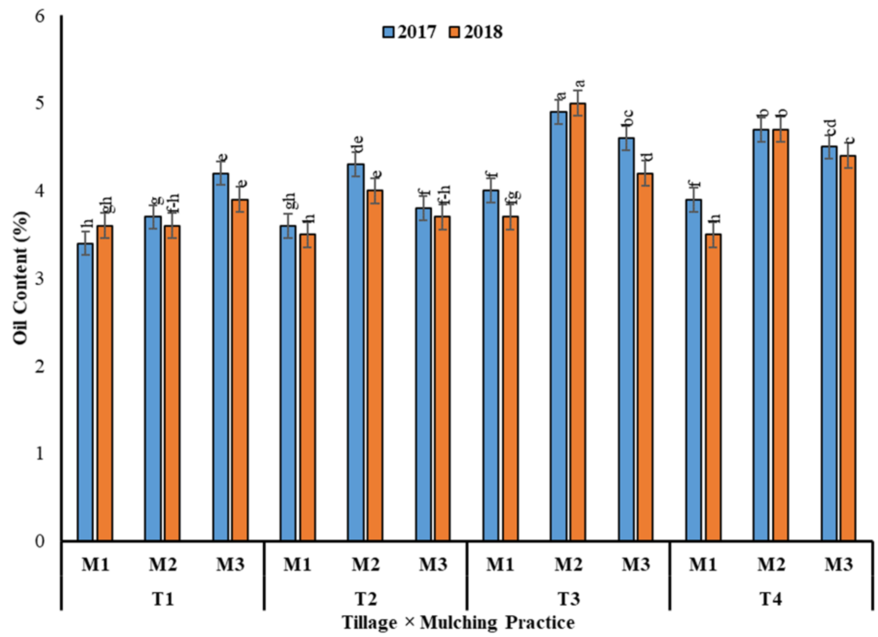


**Fig. 5:** The effects of tillage × mulching practices on maize oil content (%)
T1: Zero Tillage, T2: Cultivator + Planking, T3: MB Plough + cultivator + planking, T4: Chisel plough + cultivator + planking, M1: No mulching, M2: Polythene mulch and M3: Sorghum straw mulch, Bars (treatment mean ± standard error, n = 3) sharing different lettering for a parameter above the bar are different significantly ($P \leq 0.05$) by the Tukey's HSD test within same year

Cob length was significantly affected by tillage and mulching treatments. Chisel plough + cultivator + planking resulted in the longest cobs (19 cm and 22 cm in 2017 and 2018, respectively), which was 27% and 22% longer than zero tillage (15 cm and 18 cm in 2017 and 2018, respectively). Straw mulch resulted in 13% and 11% longer cobs (17 cm and 20 cm in 2017 and 2018, respectively) compared to polythene mulch treatment (16.1 cm and 19.7 cm in 2017 and 2018, respectively), and 6% and 5% longer cobs compared to the control treatment (16 cm and 19 cm in 2017 and 2018, respectively). The number of grain rows per cob was significantly affected by tillage and mulching practices. Chisel plough + cultivator + planking resulted in 13% and 12% more grain rows (16.8 and 17.1 in 2017 and 2018, respectively) than zero tillage (14.8 and 15.1 in 2017 and 2018, respectively). Straw mulch resulted in 7% and 8% more grain rows (15.83 and 16.26 in 2017 and 2018, respectively) compared to polythene mulch treatment (15.6 and 16.0 in 2017 and 2018, respectively), and 3% and 4% more grain rows compared to control treatment (15.4 and 15.8 in 2017 and 2018, respectively) (Table 2).

The number of grains per cob was significantly affected by tillage and mulching practices. Chisel plough + cultivator + planking resulted in 47% and 46% more grains per cob (584 and 613 in 2017 and 2018, respectively) than zero tillage (397 and 420 in 2017 and 2018, respectively). Straw mulch resulted in 29% and 28% more grains per cob (514 and 536 in 2017 and 2018, respectively) compared to zero tillage, and 12% and 10% more grains per cob compared to polythene mulch treatment (488 and 517 in 2017 and 2018, respectively), and 12% and 8% more grains per cob compared to the control treatment (457 in 2017 and 496 in 2018). The 1000-grain weight was significantly affected by tillage and mulching practices. Chisel plough + cultivator + planking produced the highest 1000-grain weight (273 g and 279 g in 2017 and 2018, respectively), which was 10% and 11% higher than zero tillage (248 g and 253 g in 2017 and 2018, respectively). Straw mulch resulted in a 1000-grain weight that was 6% and 7% higher than zero tillage, and 2% and 1% higher than polythene mulch treatment (261 and 266 in 2017 and 2018, respectively), and 4% and 2% higher than the control treatment (256 in 2017 and 263 in 2018) (Table 2).

Grain yield was significantly affected by tillage and mulching practices. Chisel plough + cultivator + planking resulted in the highest grain yield (7.02 t $ha^{-1}$ and 7.36 t $ha^{-1}$ in 2017 and 2018, respectively), which was 45% and 40% higher than zero tillage (4.84 t $ha^{-1}$ and 5.26 t $ha^{-1}$ in 2017 and 2018, respectively). Straw mulch led to a 6% and 4% higher grain yield (6.23 t $ha^{-1}$ and 6.58 t $ha^{-1}$ in 2017 and 2018, respectively) compared to polythene mulch treatment (5.9 t $ha^{-1}$ and 6.3 t $ha^{-1}$ in 2017 and 2018, respectively), and 9% and 8% higher grain yield compared to the control treatment (5.7 t $ha^{-1}$ and 6.1 t $ha^{-1}$ in 2017 and 2018, respectively). Stalk yield was significantly affected by tillage and mulching practices. Chisel plough + cultivator + planking produced the highest stalk yield (12.1 t $ha^{-1}$ and 12.7 t $ha^{-1}$ in 2017 and 2018, respectively), which was 32% and 28% higher than zero tillage (9.16 t $ha^{-1}$ and 9.92 t $ha^{-1}$ in 2017 and 2018, respectively). Straw mulch produced a 3% and 2% higher stalk yield (10.95 t $ha^{-1}$ and 11.64 t $ha^{-1}$ in 2017 and 2018, respectively) compared to polythene mulch treatment (10.6 t $ha^{-1}$ and 11.3 t $ha^{-1}$ in 2017 and 2018, respectively), and 8% and 6% higher stalk yield compared to the control treatment (10.1 t $ha^{-1}$ and 11.0 t $ha^{-1}$ in 2017 and 2018, respectively) (Table 3).

Biological yield was significantly affected by tillage and mulching practices. Chisel plough + cultivator + planking produced the highest biological yield (19.2 t $ha^{-1}$ and 19.9 t $ha^{-1}$ in 2017 and 2018, respectively), which was 45% and 35% higher than zero tillage (13.2 t $ha^{-1}$ and 14.7 t $ha^{-1}$ in 2017 and 2018, respectively). Straw mulch produced a 5% and 4% higher biological yield (17.1 t $ha^{-1}$ and 17.8 t $ha^{-1}$ in 2017 and 2018, respectively) compared to polythene mulch treatment (16.3 t $ha^{-1}$ and 17.2 t $ha^{-1}$ in 2017 and 2018, respectively), and 10% and 7% higher biological yield compared to the control treatment (15.5 t $ha^{-1}$ and 16.6 t $ha^{-1}$ in 2017 and 2018, respectively) (Table 3).

**Harvest index (%)**

Although the harvest index varied among tillage systems, these differences were not statistically significant. Chisel plough + cultivator + planking tended to result in a higher harvest index (37.60% and 37.81% in 2017 and 2018, respectively) compared to other tillage systems, although this difference was not statistically significant. In contrast, zero tillage systems tended to result in lower harvest indices (35.43% and 35.84% in 2017 and 2018, respectively). Regarding mulching practices, no significant differences in harvest index were observed among treatments. However, in 2017, the no-mulching treatment tended to result in a higher harvest index (36.87%), while in 2018, plastic mulching tended to result in a lower harvest index (36.65%). The interactive effect of tillage and mulching on harvest index was not statistically significant (Table 3).

**Quality attributes**

The protein content of maize was significantly influenced by the interactive effect of tillage systems and mulching practices. The data revealed that the combination of chisel plough + cultivator + planking and polythene mulch resulted in significantly higher protein content (9.83% in 2017 and 9.94% in 2018) compared to other treatments. This represented a 44% and 40% increase in protein content compared to the lowest values obtained under zero tillage with no mulching (6.85% in 2017 and 7.08% in 2018). Similarly, the oil content of maize was also significantly affected by the interactive effect of tillage practices and mulching treatments. The highest oil content (4.91% in 2017 and 4.97% in 2018) was obtained from MB Plough + cultivator + planking combined with polythene mulch, representing a 44% and 42% increase compared to the minimum oil percentages (3.42% in 2017 and 3.50% in 2018) found in maize sown under zero tillage without mulch and tine cultivator without mulch, respectively. These findings suggest that the combination of deep ploughing and polythene mulch can significantly enhance the protein and oil content of maize, highlighting the importance of optimizing tillage and mulching practices to improve maize quality (Fig. 4-5).

**Water input and water use efficiency**

The total water input (rainfall + irrigation) varied significantly across tillage systems and mulching treatments in both 2017 and 2018. The highest water input was recorded in chisel plough + cultivator + planking with 595 mm, which was 2.7% higher than the minimum value recorded in zero tillage with 579 mm. Straw mulch treatment received the highest water intake, with 595 mm and 599 mm in 2017 and 2018, respectively. This was 1.6% and 1.8% higher than the control treatment, which received 583 mm and 588 mm in 2017 and 2018, respectively. The interaction of tillage and mulching treatments significantly influenced the total water input in 2017, but not in 2018. In 2017, the combination of chisel plough + cultivator + planking and straw mulch resulted in the highest water input, with 610 mm, which was 4.3% higher than the lowest value recorded in the combination of zero tillage and control treatment, with 585 mm (Table 3).

Water use efficiency (WUE) was significantly influenced by tillage and mulching treatments. Deep tillage chisel plough + cultivator + planking showed the highest WUE, with 14 kg $ha^{-1}$ $mm^{-1}$ in 2017 and 16 kg $ha^{-1}$ $mm^{-1}$ in 2018. This was 27% and 33% higher than the minimum WUE recorded in zero tillage with 11 kg $ha^{-1}$ $mm^{-1}$ and 12 kg $ha^{-1}$ $mm^{-1}$ in 2017 and 2018, respectively. Straw mulch treatment also showed the highest WUE, with 14 kg $ha^{-1}$ $mm^{-1}$ and 15 kg $ha^{-1}$ $mm^{-1}$ in 2017 and 2018, respectively. This was 16.7% and 15.4% higher than the control treatment, which had a WUE of 12 kg $ha^{-1}$ $mm^{-1}$ and 13 kg $ha^{-1}$ $mm^{-1}$ in 2017 and 2018, respectively (Table 3).

**Economic analysis**

The economic analysis revealed significant variations in the costs and returns of different treatments. The total cost of production ranged from US$747 to US$1087 per hectare, with the highest cost incurred by treatment $T_4M_3$. In contrast, the net income ranged from US$113 to US$719 per hectare, with treatment $T_4M_3$ yielding the highest net income. The benefit-cost ratio (BCR) also varied across treatments, with $T_4M_3$ showing the highest BCR of 1.82. A comparison of the treatments revealed that $T_4M_3$ outperformed the control treatment ($T_1M_1$) in terms of net income, with a percent increase of 146.5%. This suggests that the combination of treatment $T_4$ and management practice $M_3$ resulted in the most profitable outcome. In contrast, treatment $T_2M_2$ incurred the lowest net income, with a percent decrease of 61.2% compared to the control treatment. These results highlight the importance of selecting the optimal treatment and management practice combination to maximize economic returns in maize production (Table 4).

## Discussion

The influence of tillage on maize growth, yield, and yield attributes is a critical aspect of agricultural research. Deep tillage treatments significantly influenced maize growth, yield, and yield attributes by improving soil physical properties, such as porosity and water infiltration (Borghei *et al*. 2008; Wasaya *et al*. 2011). This led to better root growth and nutrient uptake, resulting in higher plant height, cob length, grain rows/cob, grains/cob, 1000-grain weight, and yields compared to other tillage treatments and zero tillage (Wang *et al*. 2016; Feng *et al*. 2018; He *et al*. 2018; Wang *et al*. 2022). Deep tillage also improved soil fertility and increased crop yields by increasing the accumulation of organic carbon in topsoil, improving soil structure, and enhancing water retention performance (Wang *et al*. 2016; Chen 2021; Yang *et al*. 2023). This led to increased biomass yield, grain number per ear, and 1000-grain weight of crops, resulting in higher grain yields (Feng *et al*. 2018). In contrast, zero-tillage treatments resulted in lower plant height, cob length, grain rows/cob, grains/cob, 1000-grain weight, and yields compared to deep tillage treatments due to increased soil bulk density, reduced emergence rate, and inhibited root growth (Memon *et al*. 2013; Liu *et al*. 2014; Ren *et al*. 2018). The combination of deep tillage and straw mulch resulted in the highest maize yield and quality, likely due to the improved soil physical properties, increased nutrient uptake, and enhanced water use efficiency resulting from deep tillage, as well as the benefits of straw mulch (Silva and Cook 2003; Jordan *et al*. 2010).

The results of this study demonstrate the significant influence of mulching treatment on maize crop growth, yield, yield attributes, and quality. The use of straw mulch, in particular, was found to have a profound impact on maize production. Straw mulch led to significantly taller plants, with a height increase of 7% and 6% compared to the control treatment in 2017 and 2018, respectively. This increase in plant height can be attributed to the improved soil moisture retention and reduced soil temperature fluctuations associated with mulching (Silva and Cook 2003; Jordan *et al*. 2010). The improved soil moisture retention and reduced soil temperature fluctuations associated with straw mulch also led to increased yield attributes, including cob length, grain rows per cob, and grains per cob. Straw mulch resulted in a 13% and 11% longer cob length, 7% and 8% more grain rows per cob, and 29% and 28% more grains per cob compared to polythene mulch treatment in 2017 and 2018, respectively (Ehsanullah *et al*. 2015). These improvements in yield attributes ultimately led to a 6% and 4% higher grain yield compared to polythene mulch treatment in 2017 and 2018, respectively. The use of straw mulch also improved maize quality, with significant increases in protein content and oil content compared to polythene mulch treatment. These improvements in maize quality can be attributed to the improved soil moisture retention and reduced soil temperature fluctuations associated with mulching, which allow for more efficient plant growth and development (Rafiq *et al*. 2010). Mulching also helps to promote soil biota activity, retain soil organic matter, and reduce soil erosion, all of which contribute to improved soil fertility and increased crop quality (Boomsma *et al*. 2009; Sekhon *et al*. 2019). Overall, the results of this study demonstrate the significant influence of mulching treatment on maize crop growth, yield, yield attributes, and quality, highlighting the potential benefits of straw mulch for improving maize production.

The economic analysis of the study revealed that deep ploughing with straw or polythene mulch was the most profitable treatment, resulting in the highest net income and Benefit Cost Ratio (BCR). This can be attributed to the improved soil physical properties and increased crop yield associated with deep ploughing (Borghei *et al*. 2008; Tao *et al*. 2013, 2015). Deep ploughing breaks up compacted soil layers, improves soil aeration, and increases soil water infiltration, leading to better root growth and nutrient uptake. The use of straw mulch in combination with deep ploughing further enhanced the economic benefits of maize production. Straw mulch conserves soil moisture, suppresses weeds, and regulates soil temperature, leading to improved crop growth and yield (Sharma *et al*. 2010). Additionally, straw mulch reduces soil erosion and improves soil organic matter content, leading to long-term sustainability of maize production (Wang *et al*. 2012). In contrast, the lowest net income and BCR were recorded with zero tillage and polythene mulch, likely due to the lower crop yield and higher cost of production, which was driven by the high cost of polythene mulch (Diaz 2000). Additionally, the lack of tillage may have resulted in lower soil fertility, leading to reduced crop yields and lower net income. The adoption of deep ploughing with straw mulch can lead to increased maize yields, improved soil health, and enhanced economic benefits for farmers. This can contribute to food security, poverty reduction and sustainable agricultural development.

The results of this study demonstrate that deep tillage and straw mulch can significantly enhance water use efficiency (WUE) and reduce water consumption in maize production. These findings are consistent with previous studies, which have shown that conservation tillage and mulching practices can improve soil water storage capacity and WUE (Yin *et al*. 2015; Bai *et al*. 2019; Sun *et al*. 2020). The use of straw mulch as a conservation tillage measure can contribute to improved soil physical properties, regulated soil hydrothermal conditions, and increased soil organic matter content (Yingchen *et al*. 2014; Liu *et al*. 2019). By improving soil water storage capacity, straw mulch can ensure a sufficient water supply during critical periods of crop growth, alleviate water stress, and improve crop yield and WUE. Our results also indicate that the interaction between tillage and mulching practices can significantly impact water consumption.

## Conclusion

This study highlights that optimizing tillage and mulching practices can substantially enhance maize yield, quality, water use efficiency, and economic returns. Deep ploughing combined with straw mulching produced a 535% higher net income (US$ 719/ha) and a 64% greater benefit–cost ratio (BCR) of 1.82, compared to zero tillage with plastic mulch, which yielded only US$ 113/ha and a BCR of 1.11. Straw mulch increased maize yields by 4–6% over plastic mulch, achieving 6.23–6.58 t/ha during the 2017–2018 seasons. This combination also improved grain quality, increasing protein content to 9.83–9.94% and oil content to 4.91–4.97%. Overall, the results suggest that deep ploughing with straw mulch is a promising, sustainable approach for boosting maize productivity, resource efficiency, and profitability in semi-arid regions.

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## Author Contributions

IA conceived and formulated the project, conducted research, collected and analyzed the data and wrote the master copy of manuscript. RNA supervised the study and edited the manuscript. ZA and MAUH critically revised and finalized the final version of paper.

## Conflict of Interest

The authors declared that there was no conflict of interest that could influence the current study.

## Data Availability

Data given in this paper will be available at fair request to the corresponding author.

## Ethics Approval

Not applicable to this paper.

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