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Effect of Tillage Systems and Soil Mulching on Soil Temperature at Different Depths during the Growth of Maize (Zea mays L.) in a Semi-Arid Environment

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Abstract:

Soil temperature is an essential factor influencing heat transfer within agricultural fields, varying primarily according to soil management systems. This study focused to investigate and study the effect of soil preparation methods and mulch used types on soil temperature at different depths during the plant growth stages of maize in an arid area. The field experiment was conducted at the Wasit Governorate Agriculture Directorate / Agricultural research station, in the Al-Kardhiya area, using a structured panel layout. The study included five soil preparation systems: no-till, reduced tillage, straw-covered tillage, conventional tillage, and deep tillage with rotavator. Three mulch types were used: organic mulch with wood shavings, inorganic mulch with gravel, and a no-mulch treatment. Soil temperature at depths of 0, 5, 10, 15, and 20 cm was measured at regular intervals times throughout the growing season. No statistical analysis was done; description and graphical interpretation were done. The results showed that the surface layer (0 cm depth) captured the highest temperatures during the germination stage, and then gradually decreased with advancing growth stages; this is happened due to many factors such as mainly increased plant shading. Deep tillage with clotting but without mulch resulted in higher temperatures at all depths, while tillage with straw and organic mulch (wood shavings) reduced soil temperatures and increased thermal stability. The results demonstrate that integrated conservation tillage with organic mulch can mitigate soil temperature fluctuations and enhance thermal stability, providing a practical strategy for improving soil management and supporting crop production in arid regions.

Keywords: *straw, mulching system, soil temperature, tillage system.*

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1. Introduction

Soil temperature is a fundamental property that influences how heat is transferred within its layers. Temperature is measured in degrees Celsius or Kelvin (Ben Nacer et al., 2025). Soil temperature is primarily affected by solar radiation, the main source of thermal energy, as well as other factors including soil management practices such as tillage and mulching, and physical properties of the soil such as color, texture, and moisture content. Water contributes to maintaining stable soil temperature by reducing thermal fluctuations and increasing thermal stability (Al-Lam and Al-Saadoun, 2020; Rios-Arriola et al., 2023).

Soil temperature is a key factor that directly affects agricultural processes. It controls heat transfer and water movement within the soil, impacting seed germination, root growth, and crop development (References). The temperature difference between the surface and subsurface layers of the soil affects the upward and downward movement of heat, influencing thermal equilibrium and soil water content (Sauer and Peng, 2020). Numerous studies have shown that different soil management methods can significantly influence soil temperature. For example, conventional tillage leads to higher soil temperatures during daylight hours due to increased surface exposure and reduced organic matter content, while conservation tillage systems maintain relatively low temperatures by minimizing surface disturbance and keeping crop residues covering the surface (Shen et al., 2018; Wang et al., 2024). Covering the soil surface during dry seasons also contributes to maintaining lower temperatures during peak hours compared to uncovered soil (Nurzadeh Namaghi et al., 2018; Posari et al., 2023).

On the other hand, the results of the study by Han et al. (2025) showed that the use of inorganic mulch or natural minerals, such as gravel, contributes to stabilizing soil surface temperature and reducing its daily fluctuations by reflecting some solar radiation and limiting heat loss at night. The study also demonstrated a close relationship between soil moisture content and temperature under inorganic mulch. Soil moisture retention slows the rise in daytime temperature, while the soil maintains relatively higher temperatures at night, providing a more stable thermal environment. The results also indicate that the thermal response of mulched soil is influenced by solar radiation, air temperature, and wind speed as climatic factors, although the effect of these factors is less pronounced compared to unmulched soil. Similarly, the studies by Shen et al. (2018) and Dai et al. (2021) confirmed that adopting a no-till farming system with the use of surface mulch improves soil temperature stability, positively impacting crop productivity in arid environments. Despite our well-established knowledge of individual practices, there are still significant knowledge gaps. Many studies have evaluated tillage and mulching system in isolation, often focusing solely in soil surface temperature dynamics. However, the thermal environment experienced by plant root and soil biota with soil depths, and interactive effect of combined tillage and mulching systems on vertical temperature gradient from top soil to the deeper horizons remains poorly quantified, especially with semi-arid conditions in semi-arid areas. Furthermore, the temporal evaluation of this gradient across the key crop growth stages, from germination to maturity is not well documented. Filling this gap is essential for developing tailored soil management practices that optimize the root-zone thermal environment. As a result, this study focused on evaluating the effect of tillage systems and surface mulching types on soil temperature dynamics throughout the growth stages of maize (Zea mays L.) at different depths under semi-arid conditions such as Iraqi conditions, using both descriptive and graphical analysis.

2. Materials and Methods

2.1 Experimental Site

The field experiment was conducted in the fields of Wasit Governorate Agriculture Directorate/ the Agricultural Research Station fields, these fields are located in the Al-Kardhiya area within longitude of 45°54′7.31″E and latitude of 32°32′21.15″N, with an altitude of 25 meters ASL. According to the USDA soil texture classification system, the studied soil at the experimental site was a silty clay loam texture soil, Table 1.

2.2 Climate

The climate of Kut, Iraq, is characterized by a long, hot, and dry summer and a short, relatively cool winter. Most areas experience very high temperatures during the summer, sometimes exceeding 50°C. Weather conditions were monitored during the growing season, with an average air temperature of 41.51°C, an average relative humidity of 27.74%, and high levels of solar radiation (average solar radiation of 744.54 $W.m^{-2}$) and an average wind speed of 2.07 $m.s^{-1}$.

2-3 Experimental Design and Implementation Procedures

The land was prepared before planting, and the physical and chemical properties of the field soil were analyzed as shown in Table (1). The experiment was designed as a split-plot arrangement within a randomized complete black design (RCBD), with tillage systems assigned to the main plots and soil mulching systems to sub-plots.
The experiment included five tillage systems:
The main plot factor includes five tillage systems were used:

1. No-tillage or as control treatment (P1): without any soil disturbance
2. Reduced tillage (P2): single pass with disc harrow to depth about 12.5 cm
3. Straw-covered (P3): Straw was spread at 13.5 Kg/ experimental unit and subsequently incorporated using a disc harrow.
4. Convectional tillage (P4): Using a moldboard plough to depth to 20 cm.
5. Depth tillage with pulverization (P5): Using moldboard plow with Rotavator plough to depth > 20 cm .

While, the sub-plot factor with three surface mulching treatments were applied after tillage and planting, including:

1. No mulch (M1): Bare soil surface as control treatment
2. Organic mulch (M2): Wood shavings applied at 281 g/plant.
3. Inorganic mulch (M3): Gravel (2-5 mm diameter) applied at same rate the M2 (281.25 g/plant)

The experiment comprised 45 experimental units, including from five tillage system, three mulch types, and three replicated. The total experiments area was 600 m^2 with each experimental plot measuring 9 m^2. The experiment's period extended from July 31st, 2024 to December 2nd, 2024. The yellow maize crop (*Zea mays L.*) was planted, and chemical fertilizers were added according to the recommendations of the Ministry of Agriculture. Triple superphosphate fertilizer (P_2O_5 20%) was added at a rate of 240 $kg.ha^{-1}$ before planting, and potassium sulfate fertilizer (K_2SO_4 41.5%) at a rate of 100 $kg.ha^{-1}$ before planting. Urea fertilizer (N 46%) was also added at a rate of 200 $kg.\ ha^{-1}$ in two applications, the first one month after planting and the second two months after planting.
Soil temperature was recorded for all soil treatments at of 0 or surface, 5, 10, 15, and 20 cm. Measurements were obtained daily every two hours from 7 am to 3 pm throughout the growing season. Soil temperatures were measured using portable digital soil thermometer with probe (but Motel) and installed thermocouples connected with thermometer, one instrument was placed randomly within the central row of each experimental unit.

2-4 Data analysis

We used descriptive statistics and graphical interpretation to visualize the temporal and vertical patterns of soil temperature under different soil treatments combinations. Mean soil temperature for key growth stages (germination, vegetative growth, flowering, maturity and harvest) were calculated and compared graphically. We would like to clarify that the use of descriptive and graphical analysis in this study was a deliberate and scientifically justified choice, based on the nature of the dataset and the objectives of the research. The collected data represent a complex, high-resolution structure, including repeated soil temperature measurements (seven readings per day) across five soil depths, five tillage systems, three mulching treatments, three replicates, and five crop growth stages. Such a dataset involves strong temporal dependency and multidimensional interactions, making the application of conventional statistical tests (e.g., ANOVA) less appropriate. Repeated testing over time could lead to redundancy and increased risk of statistical bias, particularly due to autocorrelation among measurements and the non-normal behavior commonly observed in soil temperature data. Following consultation with a statistical specialist, it was determined that applying traditional inferential methods under these conditions may violate key assumptions and potentially produce misleading results. Therefore, descriptive statistics and graphical analysis were adopted as a more suitable approach for accurately representing the temporal and vertical dynamics of soil temperature.

Graphical analysis effectively captured the key patterns of the study, including temporal trends from germination to harvest, differences among treatments, and the influence of soil depth on thermal behavior. Therefore, observed differences were clear, consistent, and interpretable without the need for inferential testing. Moreover, graphical analysis remains an essential tool in soil temperature research for interpreting temporal and depth-related dynamics, as demonstrated in several studies including Wang et al., (2024), where visual interpretation complements analytical methods. In conclusion, the adopted analytical approach aligns with the complexity of the data, the physical nature of the processes studied, and established practices in the literature, providing a clear and reliable interpretation of soil temperature behavior under different management systems.

TABLE 1. Some chemical and physical properties of field soil before planting

Property	**Unit**	**Soil Depth (m)**		
		0-0.10	**0.10-0.20**	**0.20-0.30**
Electrical Conductivity (EC)	dS/m	4.08	2.80	3.20
pH	-	7.48	7.42	7.39
Organic Matter	%	1.50	1.25	1.05
Bulk Density	g/cm³	1.36	1.39	1.41
Particle Density (True Density)	g/cm³	2.43	2.45	2.47
Total Porosity	%	44.03	43.27	42.92
Soil Aggregation Stability	%	15.29	2.6	1.7
Saturated Hydraulic Conductivity	cm/hr	4.6	4.3	3.9
Field Capacity (Volumetric Moisture Content)	%	37	36.3	36.7
Permanent Wilting Point (Volumetric Moisture Content)	%	17.8	15.8	15.7
Sand	g/kg soil	193	212	255
Silt	g/kg soil	471	474	452
Clay	g/kg soil	336	314	293
Soil Texture	-	Silty Clay Loam	Clay Loam	Clay Loam

3- Results and Discussion

3-1 Discussion of Soil Temperatures – Soil Surface Layer (0 cm)

The results shown in Figure (1) indicate that the topsoil temperature reached its highest values during the germination stage. This is attributed to the natural rise in atmospheric temperatures, the intensity of solar radiation, and direct exposure of the soil surface at the beginning of the season. As the growing season progressed, temperatures gradually decreased during the vegetative growth, flowering, and ripening stages, reaching their lowest levels at harvest. This is as a result of the increased shading during plant growth, continuous with the decrease in seasonal temperatures as the decline in solar radiation, this is consistent with the Al-Lame and Al-Saadoon (2020).

When analyzing temperatures according to different growth stages, it was observed that the soil during the germination stage was most susceptible to rapid heating. The uncovered treatments recorded the highest temperatures due to direct solar radiation exposure, while covering the surface helped reduce heat intensity and provide a more favorable environment for germination. During the vegetative growth stage, temperatures gradually decreased due to the partial shading caused by increased plant mass, although the uncovered treatments maintained relatively higher temperatures. With the onset of flowering, full vegetation increased soil surface shading, leading to a further decrease in temperatures, particularly in the covered treatments, which exhibited better thermal stability. This trend continued during the ripening stage, where both the seasonal decrease in temperatures and continued covering helped to limit temperature fluctuations. At harvest, the lowest temperatures of the season were recorded due to reduced solar radiation and the absence of vegetation, but the continued presence of organic mulch such as straw and sawdust helped maintain a degree of thermal stability.

General trends indicate that the uncovered treatments, such as deep tillage without mulching (P5M1) and conventional tillage without mulching (P4M1), recorded the highest temperatures throughout the season. This is attributed to the direct exposure of the soil surface and the absence of any insulating materials, which increased solar radiation absorption and led to significant temperature fluctuations, as reported by Shen et al. (2018). On the other hand, the treatments combining tillage with organic mulching (P3M2) and no tillage with organic mulching (P1M2) showed the lowest and most stable temperatures. This is due to the presence of straw residue, which reduces radiation affects the soil surface, and wood shavings which has low thermal conductivity that increases thermal resistance and reduces heat exchange with the surrounding environment; this was agreed with the results of Dai et al. (2021).

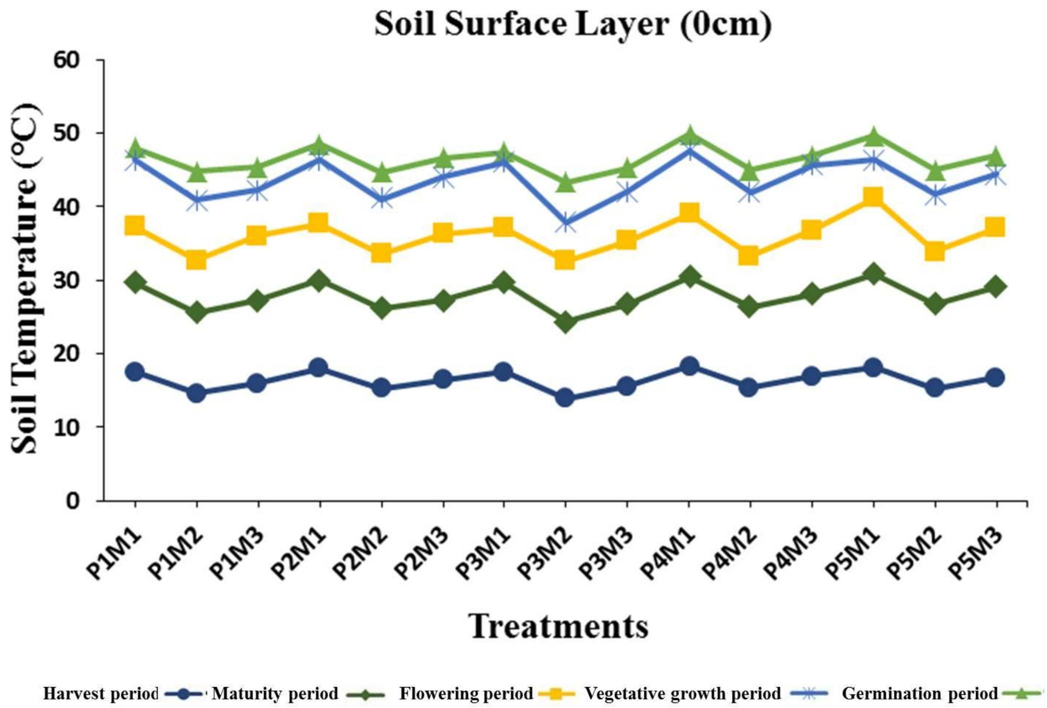

Figure (1) Effect of tillage and soil mulching systems on soil temperature (°C) of the surface layer, P1: No-till, P2: Reduced tillage, P3: Straw-covered tillage, P4: Conventional tillage, P5: Deep tillage. M1: No mulch, M2: Organic mulch, M3: Inorganic mulch.

3-2 Discussion of Soil Temperatures - 5 cm Depth

The results in Figure 2 show that soil temperatures at a depth of 5 cm followed a similar pattern to that recorded at the surface layer, gradually decreasing as the growing season progressed from germination to harvest. However, the range of thermal fluctuations was relatively smaller at this depth compared to the surface. This is attributed to the increased thermal insulation resulting from the depth, the reduced direct influence of solar radiation, and the gradual transfer of heat from the surface to the deeper layers, as noted by Rios-Arriola et al. (2023).

When analyzing temperatures according to growth stages, it was observed that during the germination stage, although fluctuations were lower compared to the surface, the temperature remained relatively high due to the accumulation and downward transfer of surface heat. Uncovered treatments, particularly P5M1, recorded the highest temperatures due to direct exposure to surface radiation, lack of insulation, and soil erosion, which accelerates surface moisture loss after irrigation. This, in turn, reduces evaporative cooling and increases heat accumulation in the soil near the surface. During the vegetative growth stage, temperatures gradually decreased due to increased vegetative shading and continued heat loss from the surface, resulting in a gradual decrease in temperature at this depth, especially in covered treatments. During the flowering stage, increased vegetation cover reduced the solar radiation reaching the soil surface, thus reducing heat transfer to deeper layers. Covered treatments, such as P3M2, maintained lower and more stable temperatures by retaining moisture and balancing radiation and evaporation. During the maturation stage, as seasonal air temperatures declined, the temperature at depth began to decrease further. Covered treatments continued to register lower temperatures than uncovered treatments, reflecting the effectiveness of organic mulching in insulating the soil and retaining moisture. During the harvest stage, the lowest temperatures of the season were recorded, and the difference between treatments was evident. Uncovered treatments continued to exhibit greater temperature fluctuations, while covered treatments remained more stable.

In general, deep tillage and tumbling treatment without covering (P5M1) recorded the highest temperatures at this depth due to exposure to surface radiation and lack of insulation, in addition to the effect of soil erosion which accelerates the loss of surface moisture. Conversely, the straw-covered tillage and organic mulch treatment (P3M2) recorded the lowest and most stable temperatures. The organic mulch acted as a radiation barrier and retained high moisture, which contributed to increased evaporation and soil cooling, thus reducing heat accumulation and transfer to deeper levels, as confirmed by Dai et al. (2021).

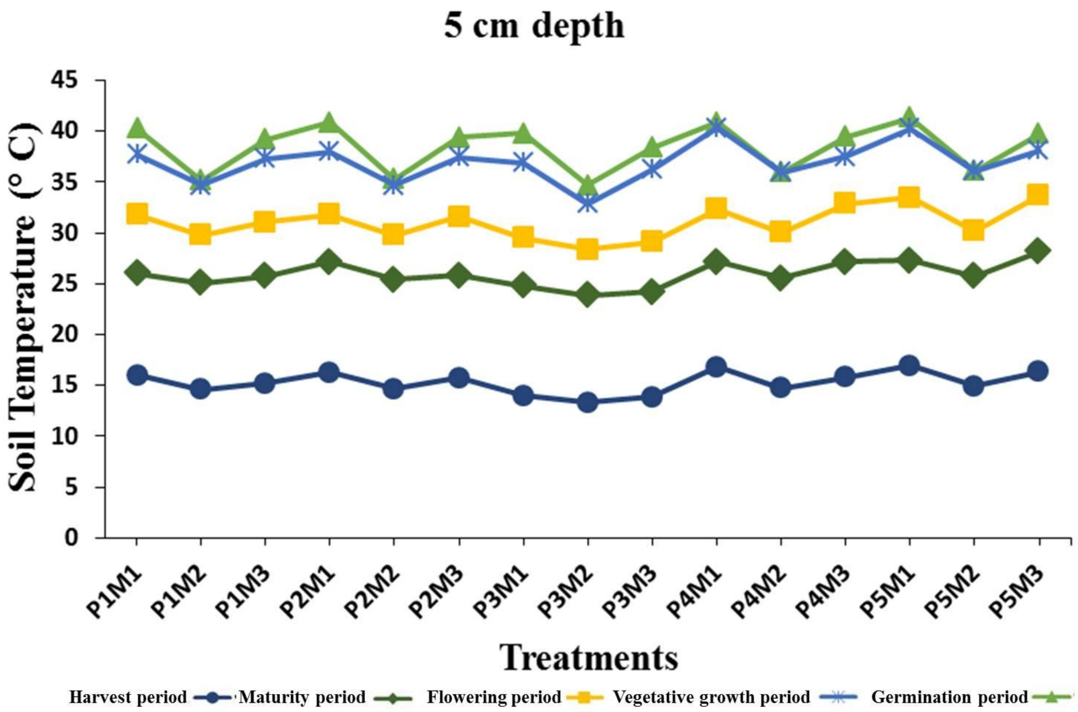

Figure (2) Effect of tillage and soil mulching systems on soil temperature (°C) at a depth of 5 cm, P1: No-till, P2: Reduced tillage, P3: Straw-covered tillage, P4: Conventional tillage, P5: Deep tillage. M1: No mulch, M2: Organic mulch, M3: Inorganic mulch.

3-3 Discussion of Soil Temperatures – 10 cm Depth

The results shown in Figure 3 indicate that soil temperatures at a depth of 10 cm were relatively lower compared to surface layers and more stable throughout all growth stages. This thermal stability is due to the reduced impact of the changes in the surface temperature as a result of the depth. Depth considered as a natural isolator which limiting sudden heat movement, and deeper soil layers keep, store and disperse heat more slowly, this is agree with what Ríos-Arriola et al. (2023) found.
The deep tillage treatment with pulverization and without mulching (P5M1) recorded the highest temperatures, indicating efficient heat transfer in loose soils exposed to direct solar radiation. The loose soil structure accelerates moisture losing, reducing evaporative cooling and directing energy towards raising the temperature, which is subsequently transferred to shallower depths.

On the other hand, the tillage treatment with organic mulching and straw (P3M2) captured the lowest and the most stable temperatures during the stage of plant growth. This is due to the reduced thermal conductivity of the soil caused by the layers of straw and wood shavings which considered as insulating layers. These organic layers minimize the transferring of the heat to layers beneath, thus maintaining a more stable thermal system within the soil, that is agreed with what stated by by Wang et al. (2024).

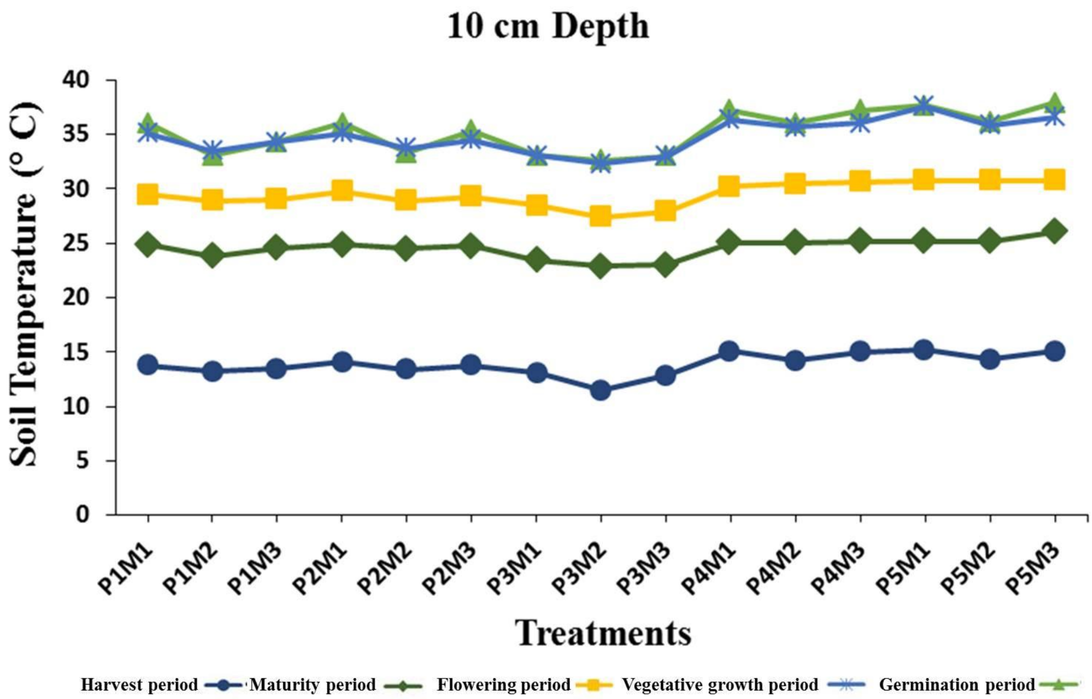

Figure (3) Effect of tillage and soil mulching systems on soil temperature (°C) at a depth of 10 cm, P1: No-till, P2: Reduced tillage, P3: Straw-covered tillage, P4: Conventional tillage, P5: Deep tillage. M1: No mulch, M2: Organic mulch, M3: Inorganic mulch

Throughout the growth stage, it was found that during germination, temperatures at this depth were relatively higher than in the next stages, due to the accumulation of surface heat and its gradual transfer to deeper soil layers. As the season progressed to the vegetative growth, flowering, and ripening stages, temperatures began to decrease gradually. However, this decrease was more gradual compared to the shallow soil layers, attributed to the slower thermal response at this depth. The harvest stage occupied the lowest temperatures, but the uncovered treatments exhibited greater thermal sequencing and fluctuations compared to the covered ones, which continued to insulate the soil and reduce its thermal differences. Thus it is clear that the effect of agricultural practices extends to the depths, although in a more subtle way compared to the surface, but organic covering is still effective in controlling the thermal system even at a depth of 10 cm, reflecting its importance in improving the thermal properties of the soil.

3-4 Discussion of Soil Temperatures – 15 cm Depth

The results shown in Figure 4 indicate that the temperature differences between growth stages at a depth of 15 cm were less pronounced compared to higher layers. This reflects increased thermal stability at this depth due to the reduced influence of surface changes. The general pattern observed at other depths continued, with the germination stage recording the highest temperatures, followed by the vegetative growth stages, then flowering and ripening, reaching the lowest values at harvest. This was agreed with what stated by Shen et al., (2018).

This temperature gradient reflects a limited surface influence with increasing depth, as the soil stores and disperses heat more slowly, thus limiting thermal fluctuations caused by atmospheric variations or direct solar radiation.

Despite this relative thermal stability, the deep tillage treatment with pulverization and no covering (P5M1) continued to record the highest temperatures at all growth stages. This indicates the continued effect of deep tillage and exposed soil in promoting vertical heat transfer to depths, thereby increasing soil temperature at this depth .

In contrast, the straw –covered tillage and organic mulch treatment (P3M2) recorded the lowest temperatures and the most stable temperatures. This is attributed to the insulating effect of the organic mulch (wood shavings and straw residues), which limits heat transfer from the surface to deeper soil zones. The high soil moisture in this treatment also contributed a reduction in the thermal conductivity which lowering the rate of heat transfer, this is consistent with the findings of Sauer and Peng (2020) and Busari et al. (2023).
Analyzing the heat behavior during the growth stages: During germination, despite the depth, temperatures remained relatively high due to the accumulation and gradual transfer of surface heat.

During the vegetation growth till the ripening, temperatures continued to decrease at a slow but steady rate, indicating a slow thermal response at this depth and the effectiveness of mulching in mitigating heat transfer. The lowest temperatures were recorded during harvest, and the uncovered treatments continued to exhibit relatively higher temperatures compared to the covered treatments. The results thus confirm that the effect of agricultural practices extends to great depths, and that the use of organic mulch remains effective in reducing heat transfer and promoting the stability of the thermal system within the soil, even at a depth of 15 cm.

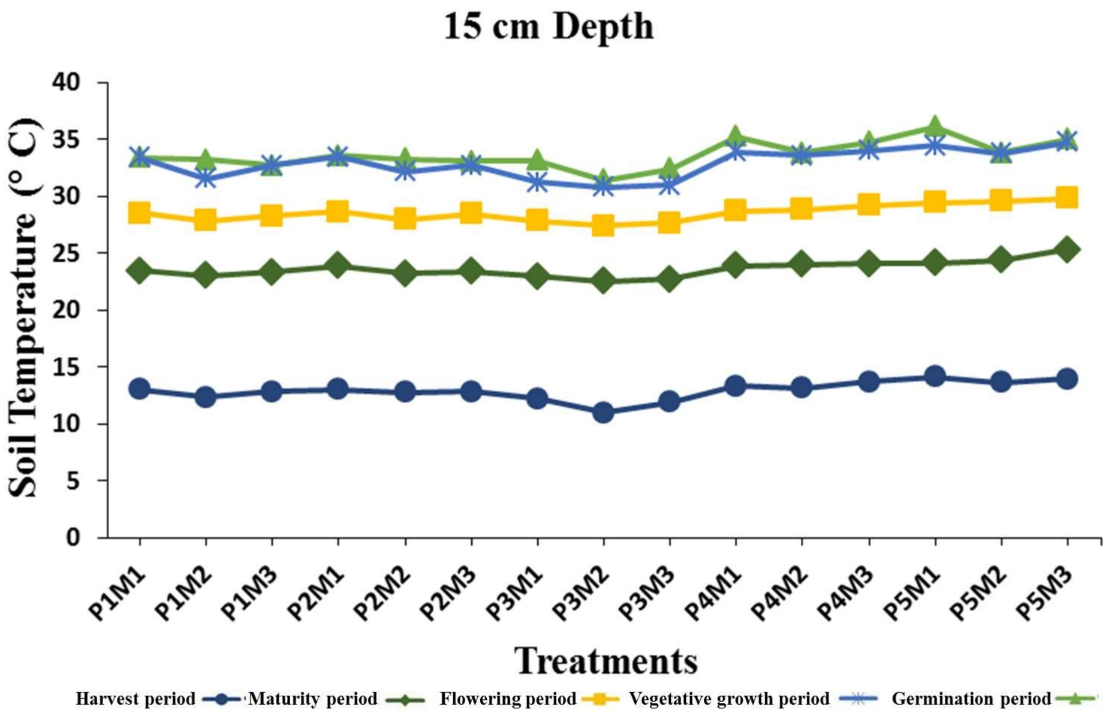

Figure (4) Effect of tillage and soil mulching systems on soil temperature (°C) at a depth of 15 cm, P1: No-till, P2: Reduced tillage, P3: Straw-covered tillage, P4: Conventional tillage, P5: Deep tillage. M1: No mulch, M2: Organic mulch, M3: Inorganic mulch

3-5 Discussion of Soil Temperatures – 20 cm Depth

The results shown in Figure 5 indicate that soil temperature at a depth of 20 cm exhibited the lowest thermal variation between growth stages compared to other depths, suggesting high thermal stability in this deep layer. This is attributed to the significantly lower effect of direct solar radiation at this depth, where the temperature depends mainly on the heat stored and gradually transferred from the upper layers, as noted by Shen et al. (2018) and Al-Lam and Al-Saadoun (2020).

Although the differences between time periods became minimal, the general pattern observed in previous depths continued, with the highest temperatures recorded during the germination stage, then gradually decreasing during the vegetative growth, flowering and ripening stages, while the lowest soil temperature values were reached at the harvest stage.

It is worth noting that while the impact of agricultural practices (such as tillage and mulching) diminishes with increasing depth, the interaction between the type of practice and soil depth remains a crucial factor in determining and controlling soil temperature. The deep tillage treatment with loosening and no mulching (P5M1) showed a clear tendency to register higher temperatures than other treatments, reflecting the continued effect of loosening exposed soil in facilitating vertical heat transfer through soil depths.

In contrast, the straw-mulched and organic mulching treatment (P3M2) maintained the lowest and most stable temperatures at this depth. This can be explained by the effectiveness of the organic mulch in hindering heat transfer due to its low thermal conductivity and high soil moisture retention, which reduces thermal conductivity and slows heat penetration to depth, as reported by Nurzadeh Namaghi et al. (2018) and Dai et al. (2021).

Thus, the results confirm that organic mulching, along with the soil structure resulting from tillage, still plays a significant role in influencing the internal thermal environment of the soil, even at depths of 20 cm, albeit to a lesser extent than in the upper layers.

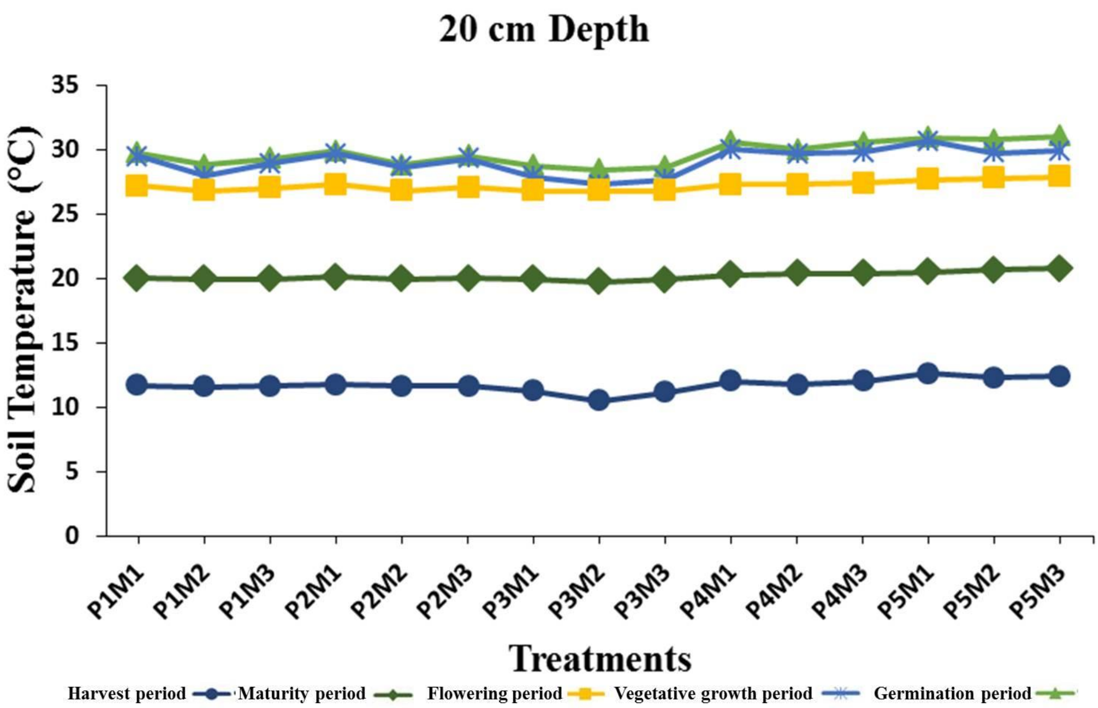

Figure (5) Effect of tillage and soil mulching systems on soil temperature (°C) at a depth of 20 cm, P1: No-till, P2: Reduced tillage, P3: Straw-covered tillage, P4: Conventional tillage, P5: Deep tillage. M1: No mulch, M2: Organic mulch, M3: Inorganic mulch

3-4 Practical implications of study

The vertical and temporal analysis reveals that soil management is function of both energy interceptions at the soil surface and heat transfer regulation within the soil profile, while soil tillage systems primarily alter the soil physical properties for heat as soil structure and soil bulk density. Soil mulching controls the energy input at boundary layer. The least favorable thermal environment for maize crop growth is semi-arid , it characterized by high peak soil temperatures and large fluctuations, was obtained by intensive tillage system that pulverizes the soil and leaves it bare (P5M1), this practice maximizes radiative heating and conductive transfer. Conversely, combining straw with covered with organic surface mulch (P3M2) having the most buffered environment. This combination successfully isolated the soil from severe atmospheric influences by providing multi-layered insulation and enhancing soil moisture content, thereby taking advantage of physical and hydrological cooling mechanisms. These results are strongly consistent with the principles of conservation agriculture, demonstrating that systems concerned with this are superior to single-agent approaches in mitigating heat stress in arid land farming systems.

4. Conclusions

The study showed that soil temperature is clearly affected by both the tillage system and the type of surface mulch. The temperature variations were mainly as a result of the interaction between soil structure disturbances caused by tillage and the insulating or thermally conductive properties provided by different mulch materials. The highest soil temperatures were recorded at all depths during the germination stage, due to the exposure of the soil surface and the high intensity of solar radiation. This was followed by a gradual decrease as growth progressed and plant shading increased. The deep tillage treatment without mulch (P5M1) resulted in the highest and most fluctuating temperatures at all studied depths. This is attributed to increased soil surface disintegration, decreased bulk density, and the absence of any form of thermal insulation. In contrast, the straw-mulched tillage treatment with organic mulch (P3M2) recorded the lowest and most stable temperatures in all soil layers, indicating the effectiveness of the accumulated surface insulation in achieving significant thermal stability within the soil . The effect of tillage and surface mulching systems gradually decreased with increasing depth, but treatments that provided composite thermal insulation remained effective in stabilizing soil temperature up to a depth of 20 cm.

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