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Meta-analysis of tillage methods and their influence on wheat productivity

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A b s t r a c t. Approximately 60% of mechanical energy consumption in mechanized agriculture is dedicated to soil tillage operations and seedbed preparation. With awareness of the adverse effects of excessive tractor traffic on farms during seedbed preparation, the issue of selecting suitable equipment and factors affecting soil compaction reduction and increasing crop yield has become increasingly important. Numerous studies have been conducted on soil tillage and its effects on wheat yield in the past. While each individual study holds value, it is necessary to examine the results of these multiple studies together to reach a conclusion regarding the factors influencing wheat yield enhancement. The aim of meta-analysis is to extract more information from existing data than what can be obtained by aggregating the results of smaller studies with one or a few statistical analyses. This research examines over 264 scientific documents (including theses, research reports, and articles) from the past decade using a meta-analytical approach. The results of this investigation indicate that: Overall, various tillage methods result in approximately a 5% reduction in wheat yield compared to the conventional method in the region, with no significant difference observed with reduced tillage methods, and deep tillage tools showing a 5% increase. Regarding soil moisture retention, an overall 5% increase was observed, with no significant difference with reduced tillage methods, a 5% increase with no-till methods, a 10% increase with reduced tillage methods, and a 15% increase with deep tillage tools. Reduced tillage is one of the best methods for preserving more soil moisture while yielding similar wheat performance to the conventional method and other tillage methods at a 95% confidence level. Considering its lower mechanical energy consumption, it is recommended for use in the country.

K e y w o r d s: conservation agriculture, tillage, crop yield, sustainable agriculture

1. INTRODUCTION

Wheat stands as the third most significant grain crop globally, with an annual cultivation spanning over 200 million ha and yielding in excess of 760 million metric tons. This vital crop contributes approximately 19% of the world's calorie intake and 21% of its protein consumption, as per data from the Food and Agriculture Organization (FAO) in 2022 (Wang *et al.*, 2023).

Agriculture is one of the most essential practices for most plants, with some of its objectives including preparing an optimal structure for seed germination and root growth, facilitating rapid moisture penetration and retention, ensuring adequate air capacity and exchange within the soil, controlling weeds, and managing plant residues. Conventional tillage refers to a series of common and traditional soil cultivation operations utilized in a specific geographical region to create a suitable seedbed for planting, often involving intensive soil plowing and turning (Lal,

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2017; Findura *et al.*, 2022). In this type of tillage, the entire soil surface is disturbed, leaving less than 15% of plant residues on the soil surface. Implements such as moldboard plows, discs, or heavy-duty discs are often used for its execution, accompanied by high fuel consumption in tractors (Busari *et al.*, 2015). Moreover, conventional tillage entails higher depreciation, repair, and maintenance costs for tractors and soil implements, consequently increasing expenses and rendering it economically inefficient. Conventional tillage increases greenhouse gas emissions and exacerbates air warming. Additionally, in this method, weed control is either mechanically performed using cultivators, which, due to extensive soil disturbance by mechanical implements, heightens the risk of erosion and dust emissions, or chemically using herbicides, leading to environmental pollution and increased costs (Teodoro-Morrison *et al.*, 2014; Wachira *et al.*, 2014; Fanigliulo *et al.*, 2021).

Conservation tillage emerged in Europe and America as a substitute system for moldboard plowing starting from the 1940s. It gained attention due to the droughts and was implemented to prevent soil erosion caused by water and wind. Non-plow agriculture was introduced for the first time as a means to address these challenges. In contemporary agriculture, conservation practices such as reduced tillage, cover cropping, and crop rotation are extensively embraced. These methods offer a sustainable approach to farming, minimizing environmental impact while sustaining crop yields (Allam *et al.*, 2021). Therefore, these practices are essential for designing sustainable farming systems. Implementing such techniques can lead to enhanced agro-ecological services, optimizing productivity and profitability while mitigating environmental harm. Conservation agriculture practices lead to the enhancement of natural biological processes in the soil's sub-surface and surface layers. This improvement is achieved by reducing soil disturbance and manipulation and transitioning from conventional plowing to minimum tillage (Verhulst *et al.*, 2010). Conservation tillage, incorporating reduced or minimum tillage (RT), mulch tillage, ridge tillage, and no-tillage systems, is increasingly appealing to farmers. This is due to its ability to reduce labor and fuel expenses, given that plowing is the most energy-intensive process in arable crop production(Allam *et al.*, 2021). Various studies have indicated that agricultural systems reliant on reduced mechanical soil disturbance offer a viable alternative to conventional tillage (CT) in terms of their effects on soil and the environment (Wang *et al.*, 2017; Peigné *et al.*, 2018).

Numerous studies have showcased the effectiveness of conservation tillage in enhancing crop yields, improving soil physical and chemical characteristics, and reducing both energy consumption and production expenses (Bai *et al.*, 2022). Shahzad *et al.* (2016) demonstrated that the interaction among various tillage methods and systems significantly influenced soil bulk density, total porosity, as well as the algometric growth and yield of wheat. Singh *et al.* (2016) have demonstrated that implementing conservation agriculture practices, including zero tillage, residue retention and, dry direct seeding rice can enhance yields, decrease expenses, and augment farmers' profits within the rice-maize system. Pittelkow *et al.* (2015) found that conservation tillage practices, coupled with residue incorporation and crop diversification, notably enhanced rain fed crop productivity in arid conditions.

By the mid-20th century, the overwhelming quantity of research reports compelled researchers to contemplate the development and application of methods for synthesizing the resulting findings (Gurevitch *et al.*, 2018). The term Meta-analysis was first introduced by Gene Glass (1976) in the American Educational Research Association. The goal of meta-analysis is to obtain more information than what is available by synthesizing the results of smaller studies and one or more statistical analyses. This way, findings that may not be revealed in smaller studies can be obtained by meta-analysis through combining dozens of smaller studies (O'Rourke, 2007). The need to summarize various research studies has long been recognized. To this end, some researchers undertake writing review articles where a specific topic, extensively studied, is reviewed, and efforts are made to summarize its impact. However, in most cases, no statistical methods are employed to examine and synthesize the research results.

The aim of this study is to evaluate the efficacy of different tillage methods on wheat yield through the application of meta-analysis. This research aims to provide a comprehensive analysis of the effects of various tillage techniques on wheat production, contributing to a better understanding of sustainable agricultural practices and informing decision-making for farmers and policymakers. The research process for meta-analysis is based on collecting and extracting relevant data within a suitable timeframe, as chosen in this study for the last decade. Subsequently, data are gathered from various sources, including articles, final reports of research projects, theses, and dissertations. Finally, statistical analysis is conducted using meta-analysis methods to compare different approaches with the baseline method, which in this study was conventional tillage.

2. MATERIALS AND METHODS

In this study, various tillage methods, including conventional tillage (comprising the use of moldboard plow and tandem disc harrow), reduced tillage, no-till, shallow tillage, and subsoiling, have been investigated. The effects of each of these methods on wheat performance and soil moisture retention have been examined both individually and collectively.

Meta-analysis is an appropriate method for systematically combining the results of different studies to achieve a more accurate estimation of reality. It can provide a unified conclusion to a set of research that may sometimes report conflicting results, thus resolving discrepancies. The population of the current research includes all research designs, projects, published articles, master's theses, and doctoral dissertations related to the study of tillage and its effects on grain performance in the country over the past decade. Each of the factors mentioned in the performance of grains was examined and analyzed using the meta-analysis method, and ultimately, comprehensive guidelines for use in various regions of the country were provided. The results are applicable to farmers, researchers, and policymakers alike.

The criteria for meta-analysis included: 1) the presence of both the keywords "tillage" and "wheat performance" in the title, and 2) studies conducted over the past decade. Content analysis checklist was employed to select studies meeting the criteria, and the necessary information for meta-analysis was extracted. Figure 1 presents the statistics of the number of sources collected by region. In each of the studies, different variables have been considered as independent and dependent variables.

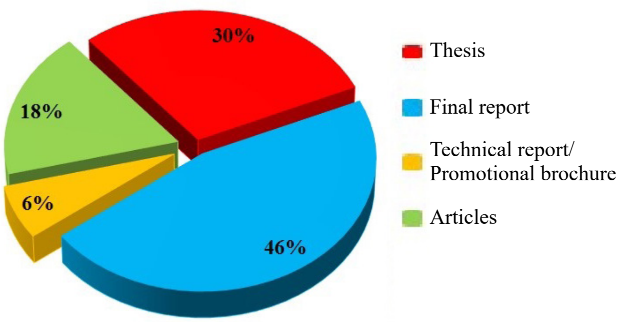

Fig. 1. Sources and their categorization.

In this approach, attention has been paid not only to the differences between studies but also to the variance of effect sizes. To this end, in each study, the mean values, standard deviations, and sample sizes (number of replicates in each experiment) for both the control and treatment groups were extracted and presented accordingly. Subsequently, following data categorization, the response ratio (R) was calculated as shown in Eq. (1), and thereafter, the logarithm of the response ratio was also obtained (Hedges *et al.*, 1999):

$$R = \frac{\overline{\overline{x_E}}}{xc}, \quad (1)$$

in which: $\overline{x}_E$ represents the average value of the trait in the treatment group, and x_C denotes the mean value of the trait in the control group. There are two reasons why it is better to present the response ratio in terms of a linear logarithmic scale. Firstly, the linear logarithmic scale exhibits similar behavior with the standard deviations in the denominator. This concept implies that this ratio is more influenced by changes in the denominator (especially when the denominator is small), but the logarithm of this ratio equally accounts for changes in both the numerator and denominator of the fraction. The second reason is that the distribution of the response ratio (R) usually exhibits skewness, whereas the distribution of the logarithm of the response ratio (L) is typically normal. Therefore, the response ratio will be transformed into a logarithmic form as follows (Allam *et al.*, 2021):

$$L = \ln R = \ln\left(\frac{x_E}{x_C}\right). \quad (2)$$

The best approach for comparing various studies is to use the average effect of their findings. However, different studies have different levels of precision (standard errors) in estimating effect sizes. Therefore, before conducting meta-analysis, data should be weighted. Consequently, studies with higher experimental precision will have higher weights, leading to an increase in the precision of the estimated effect size. The weighted average of the logarithm of the response ratio, which creates the highest precision (lowest variance), is calculated using Eqs (3) and (4) (Allam *et al.*, 2021):

$$\overline{\ln R} = \frac{\sum_{i=1}^{n} (\ln R_i \times W_i)}{\sum_{i=1}^{n} W_i}, \quad (3)$$

$$\overline{L^*} = \frac{\sum_{i=1}^{n} (W_i \times L_i)}{\sum_{i=1}^{n} W_i}. \quad (4)$$

In this context, i represents the study number, and w represents the number of repetitions in each observation. The confidence intervals for the mean of the logarithm of the response ratio ($\ln \overline{R} = \mu_\lambda$), denoted by ($CL_U$, CL_L), can also be obtained through Eqs (5) and (6):

$$CL = \overline{L^*} \pm (-z_{a/2} \times SEM(\overline{L^*})), \quad (5)$$

$$(CL_L) \le \mu_\lambda \le (CL_U). \quad (6)$$

In the next step, the values of (μ_λ) were transformed by taking the antilogarithm. Then, the mean of these antilogarithmic values (μ_p) was compared, and confidence intervals for (μ_p) were calculated using Eq. (7):

$$\exp(CL_L) \le \mu_p \le \exp(CL_L). \quad (7)$$

Of course, it should be noted that the confidence intervals for the logarithm of the response ratio are symmetric, but the confidence intervals for the antilogarithmically transformed data (μ_p) will not be symmetric. In this equation, using this test, it will be determined which treatment has a positive effect and which treatment has a negative effect on the studied performance. Additionally, treatments that had no positive or negative effect on the above components were also identified. The extraction of mean values, standard deviations of errors, and plotting were also performed in the Microsoft Excel software.

3. RESULT

Since the focus of this research is on examining the effect of different tillage methods on wheat performance, various tillage methods were carefully extracted from all documents. These methods generally include: conventional tillage (control), reduced tillage, no-till, conservation tillage, deep tillage (subsoiling), surface tillage, and semi-deep tillage (semi-subsoiling). Typically, the conventional tillage method (control) in most studied areas nationwide involves the use of a moldboard plow and tandem disc harrow, which is suitable for wheat cultivation. By examining Fig. 2, it is inferred that contrary to common belief, overall, different tillage methods, compared to the conventional method in the region, result in approximately a 5% reduction in wheat performance.

In the no-till method, by examining the relevant yield trend in Fig. 2, it indicates approximately a 10% reduction. Investigating the yield trend associated with the use of chisel plow showed about a 4% reduction in wheat performance. However, since the yield trend intersects the zero line (conventional method), this difference is not statistically significant. Related research also supports this point (Hedayatipour and Younesi alamouti, 2018). In the surface tillage method, showing a decrease in wheat performance, because the horizontal yield trend crosses the zero line, it indicates that there is no significant difference from the conventional method at a 95% confidence level. Various studies show a slight reduction in yield, and it is essential to note that this reduction is not statistically significant at a 95% confidence level (Sadeghnezhad and Eslami, 2006).

Additionally, in Fig. 2, it is observed that the use of a disc harrow has reduced wheat performance by over 10%. As we know, rotary tillers with horizontal axes are known for disrupting surface soil and creating a relatively suitable

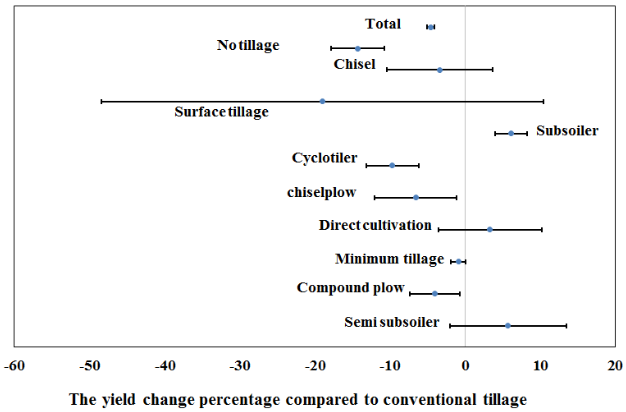

Fig. 2. Percentage changes in wheat grain yield under different tillage treatments compared to conventional tillage.

bed for cultivation while maintaining an acceptable moisture level. Therefore, considering various studies on the use of this tool, and based on the results of wheat performance as well as soil moisture retention, its recommendation is advisable (Heidary, 2013).

Upon examining Fig. 2, it is evident that the chisel plow has resulted in a nearly 5% reduction in wheat grain yield. Gholami *et al.* (2014) examined the impact of various soil management practices on soil physical properties, as well as the yield and its components of irrigated wheat. Their findings revealed significant variations in wheat yield and its components across different soil management systems. Specifically, conventional tillage yielded the highest grain production (6 825 kg ha^{-1}) compared to the no-tillage system (5 220.83 kg ha^{-1}). Moreover, the conventional tillage method resulted in the greatest thousand-grain weight (43.38 g) and crop harvest (25.57%).

In the direct seeding method, although we observe a slight increase in wheat grain yield, since its trajectory intersects the zero line, which represents the conventional method, it does not show a significant difference compared to the conventional approach. It is essential to note that direct seeding is technically considered one of the no-tillage methods. Therefore, the use of various compatible implements capable of direct seed placement could have a significant impact on wheat grain yield (Findura *et al.,* 2023; Ignaciuk *et al.,* 2024). Marakoğlu and Çarman (2012) conducted research on wheat production, comparing direct seeding, reduced tillage, and conventional tillage in Central Anatolia. Their findings revealed that the highest wheat yield was achieved through direct seeding, reaching 3 388.9 kg ha^{-1} in 2008. Conversely, the lowest wheat yield was observed with the conventional method, registering 2 290 kg ha^{-1} in 2007. Notably, direct seeding demonstrated superior performance in terms of fuel consumption, effective power requirement, field efficiency, and ultimately, wheat yield.

Figure 2 illustrates that in the reduced tillage method, the crop performance is nearly identical compared to the conventional tillage method. The use of composite plows shows a reduction of about 5%. Similar studies have also reported a slight difference in wheat grain yield when using composite plows compared to other conventional methods (Hedayatipour and Younesi alamouti, 2018).

The use of semi-subsoiler does not show a significant difference in performance compared to the conventional method. Semi-deep tillage, if performed properly, can reduce the negative effects of soil compaction. However, the use of subsoiler shows an increase in performance by approximately 5%. Soil compaction leads to negative effects that ultimately affect plant growth and result in reduced crop yield. Therefore, if the crop yield is not satisfactory, soil compaction may be one of the contributing factors that needs to be scientifically investigated and evaluated. The effect of soil tillage remains for about 3-5 years, so there is no need for re-tillage during this period. Soil tillage reduces bulk density and cone index, leading to increased soil pore space and ultimately enhancing moisture retention in the soil. This is particularly important in rain fed farms, optimizing rainwater usage. Soil tillage also increases crop yield (Odey and Manuwa, 2018).

The confidence intervals of horizontal loads indicate about 95% certainty. If the confidence intervals have reached or crossed the zero line, there is no significant difference between the traditional soil treatment and the usual soil treatment. For comparing different soil treatments with each other, if the confidence intervals have reached or crossed each other, there is no significant difference between the two treatments. In Fig. 3, since the loads have crossed the zero line and the loads of the two conditions, Irrigated and rain fed cultivation, are mixed, the difference between soil treatments on wheat performance in the two conditions of Irrigated and rain fed cultivation is not significant.

The horizontal loads indicate approximately 95% confidence. Given that the loads have crossed the zero line and the loads of the two conditions are mixed, there is no significant difference in the performance of wheat under soil treatments in both dry and wet conditions. Figure 4 shows the percentage changes in soil moisture under different soil treatments compared to conventional soil treatment. The horizontal loads indicate approximately 95% confidence. If the confidence intervals have reached or crossed the zero line, there is no significant difference between soil treatments and conventional soil treatment. For comparing different soil treatments with each other, if the confidence intervals have reached or crossed each other, there is no significant difference between the two treatments. With this description, overall, no significant difference was observed in moisture improvement between conservation tillage methods and conventional tillage, but some methods showed significant superiority over the conventional method. These methods included no-till, chisel plow, moldboard plow, and composite moldboard plow.

In the no-till method, water retention is shown to be approximately 10% higher compared to the conventional method. Interestingly, this exact amount has been confirmed by other similar research studies. In a research conducted by Ding *et al.* (2018) they investigated the effect of conservation tillage on soil water status and winter wheat yield in agricultural land and reported that during the jointing stage of winter wheat, no-tillage led to a 7.3% increase in soil water conservation, whereas subsoiling showed a decrease of -0.68%. Compared to conventional tillage, no-tillage significantly increased soil water storage in the 0-60 cm soil layer during the jointing stage. Additionally, no-tillage resulted in significant increases in soil water content across various stages (jointing, flowering, filling, and harvesting) in the 0-100 cm soil layer, while subsoiling only showed significant increases during certain stages. Moreover, no-tillage notably boosted winter wheat yield and water use efficiency, particularly in dry years. Hence, in dry conditions, no-tillage outperforms subsoiling in both soil moisture conservation and yield enhancement.

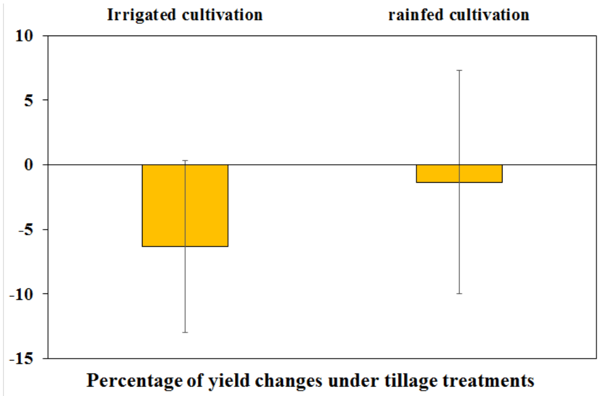

Fig. 3. Percentage of changes in wheat yield under tillage treatments compared to conventional tillage in both wet and dry conditions.

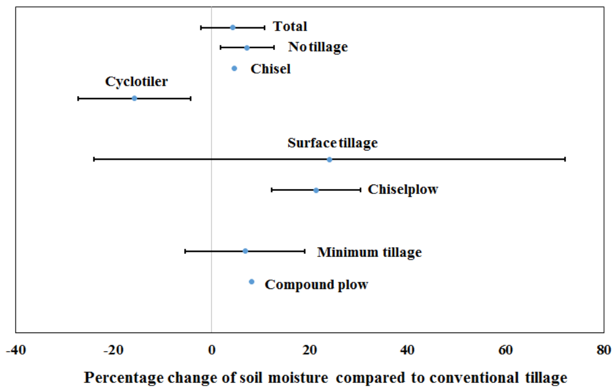

Fig. 4. Percentage of changes in soil moisture under different tillage treatments compared to conventional tillage.

The use of the chisel plow, as observed in Fig. 4, indicates approximately a 5% greater increase in moisture retention compared to the conventional method. It's worth noting that the necessary traction force for the chisel plow (a large chisel plow) in equal dimensions and under the same soil conditions is equivalent to half the force required for pulling a moldboard plow, and significantly, the remaining water retained in the soil is much higher compared to the moldboard plow. As seen in Fig. 4, the use of the cultivator will result in soil moisture retention approximately 25% higher than the conventional tillage method, yet this difference was not statistically significant. Of course, considering the nature of the soil mixing method, this finding seems logical. Other studies conducted on this tool also confirm the results (Heidary, 2013).

Considering Fig. 4, it is observed that although surface tillage appears to retain less moisture compared to the conventional method, in reality, there is no significant difference at the 95% confidence level between the cultivator tillage and reduced tillage methods. In various surface tillage methods, a wide range of moisture may remain in the soil, which depending on the tools used, may sometimes even be less than the conventional method. If this method is accompanied by residue retention on the soil surface, a significant improvement in soil moisture retention will be achieved.

The use of moldboard plow not only requires considerable pulling force but, as observed in Fig. 4, also retains a suitable amount of moisture (approximately 20% more than the conventional method) in the soil. Employing moldboard plow (small chisels) is capable of preserving adequate water reserves in the soil and, while performing suitable tillage, can lead to energy savings as well. Figure 4 demonstrates that although reduced tillage method retains soil moisture up to about 10% more than the conventional method, this difference is not statistically significant at the 95% confidence level. Similarly, to surface tillage, in this method too, maintaining plant residues on the soil surface can contribute to increased soil moisture retention.

A considerable number of studies investigating the application of composite moldboard plows in Iran have not been conducted. However, by examining the same limited number of studies and carefully analyzing Fig. 4, it appears that soil moisture retention is approximately 10% higher compared to the conventional method. Of course, considering the objectives of employing such composite plows, this amount seems reasonable.

Horizontal loads indicate approximately 95% confidence. If the confidence intervals reach or cross the zero line, there is no significant difference between conservation tillage and conventional tillage. For comparing different tillage treatments, if their confidence intervals overlap or cross, the difference between the two treatments is not significant.

Results showed that overall, conservation tillage significantly increased soil moisture retention in dry conditions, with an approximately 13% greater increase compared to conventional tillage in the country's dry regions (Fig. 5). However, soil moisture retention by conservation tillage methods did not significantly differ from conventional methods in irrigated wheat cultivation conditions, and the difference in soil moisture retention was not significant in these conditions (Fig. 5).

Horizontal loads indicate approximately 95% confidence. In dry conditions, tillage treatments had a positive and significant effect on soil moisture retention. However, in irrigated conditions, tillage treatments did not result in a significant change in soil moisture.

4. CONCLUSIONS

The results indicate that wheat grain yield under conservation tillage methods did not significantly differ from conventional tillage. However, wheat yield showed a significant increase under subsoiling conditions compared to conventional tillage, indicating improved root development

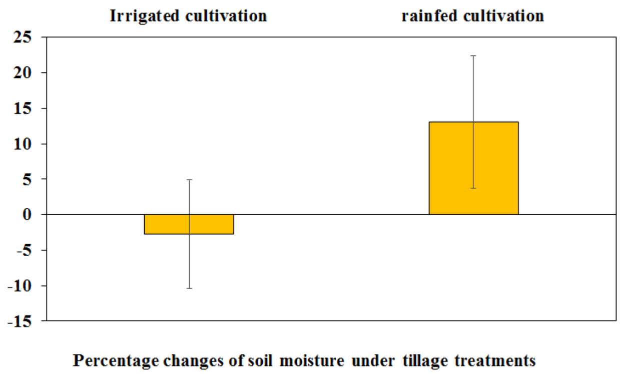

Fig. 5. Percentage of changes in soil moisture under tillage treatments compared to conventional tillage in wet and rainy conditions.

depth in these conditions, ultimately leading to enhanced wheat grain yield. The use of conservation tillage methods (no-till, chisel plow, moldboard plow, and composite moldboard plow) resulted in improved soil moisture retention compared to conventional tillage. It is worth noting that the use of cultivator and reduced tillage also improved soil moisture, although this increase was not significant compared to conventional tillage. Surface tillage also did not significantly differ from reduced tillage and cultivator methods. It should be noted that the improvement in soil moisture under dry conditions and the use of conservation tillage led to a significant increase in soil moisture compared to conventional tillage. Considering that in reduced tillage, soil tillage operations are performed with less intensity, in addition to soil moisture retention due to soil structure preservation, the amount of energy and fuel consumed by tractors will decrease. The deeper the soil tillage machine works, the greater the machine's contact area with the soil and the more energy it consumes. Furthermore, with this tillage method, the environment for soil organisms such as earthworms will be more suitable, and by preserving plant residues, the ratio of carbon to nitrogen in the soil will be within a suitable range. Additionally, the total cost of reduced tillage machines is lower compared to moldboard plows. Therefore, the use of reduced tillage methods is recommended both technically and economically.

Conflicts of Interest: The Authors do not declare any conflict of interest.

Data Availability Statement: The data presented in this study are available on request from the first author.

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