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Effects of Irrigation Frequency on Dry Matter Accumulation and Water Use Efficiency of Wheat

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Abstract Wheat (*Triticum aestivum* L.) is a globally essential cereal crop whose productivity is closely linked to water availability, particularly in water-limited regions. This study explores the effects of different irrigation frequencies on dry matter accumulation and water use efficiency (WUE) in wheat cultivation. We examined the physiological basis of biomass accumulation and analyzed how irrigation intervals influence partitioning among organs and developmental stage-specific responses. Further, we evaluated WUE in relation to irrigation frequency, considering agronomic implications and the interplay of root development, leaf structure, and molecular signaling pathways. A case study from a semi-arid wheat-growing region provided field-based insights into the impacts of irrigation frequency on yield, soil health, and practical outcomes. Our analysis highlights the trade-offs between water input and biomass productivity, emphasizing the importance of optimized irrigation scheduling. We conclude that moderate irrigation intervals can enhance WUE without severely compromising yield, though outcomes depend on local climate and soil conditions. Future research should focus on site-specific strategies using precision agriculture to improve sustainability under climate variability.
Keywords Wheat; Irrigation frequency; Dry matter accumulation; Water use efficiency; Semi-arid agriculture

1 Introduction

Wheat is one of the most important food crops in the world. It is critical to food security and agricultural development. In recent years, the increase in wheat yields is mainly due to variety improvement and the rational use of resources such as water and nitrogen (Hao et al., 2023; Ma et al., 2024). Among these resources, water plays the greatest role. Water supply directly affects the growth process of wheat, and also affects the accumulation of dry matter and the final yield. Reasonable irrigation can keep wheat photosynthesis strong and prolong the filling time, thereby improving the efficiency of water and nitrogen use (Li et al., 2018; Li et al., 2019; Lyu et al., 2020).

The time and frequency of irrigation have a great influence on the distribution of dry matter and also affect the reuse of carbon reserves. These factors are closely related to grain development and final yield (Wang et al., 2011; Huang et al., 2014). In water-scarce areas, how to arrange the irrigation time becomes particularly important. Only in this way can we achieve both increased production and resource conservation (Wang et al., 2023).

This study mainly aims to summarize recent research results on the effects of irrigation frequency on wheat dry matter accumulation and water use efficiency. We will pay special attention to several common irrigation methods, such as drip irrigation, micro-spraying and supplementary irrigation. How do these methods affect wheat physiological processes, dry matter distribution and resource utilization efficiency under different wheat varieties and different environments? By integrating research under different ecological conditions, we hope to provide some practical suggestions for future irrigation management to make wheat cultivation more productive, environmentally friendly and sustainable.

2 Dry Matter Accumulation in Wheat under Varying Irrigation Frequencies

2.1 Physiological basis of dry matter accumulation

Wheat's dry matter is mainly produced through photosynthesis. The quality of photosynthesis is closely related to the availability of water and nutrients. Irrigation can help wheat maintain a large leaf area and fast photosynthesis, and it can also slow down plant aging, thereby accelerating the accumulation of dry matter and allowing it to accumulate for a longer time, especially during the important stages of wheat growth (Li et al., 2023). Generally speaking, dry matter accumulation grows in an "S-shaped" pattern. If there is not enough water, wheat will reach the peak of accumulation earlier, but the rate and total amount of accumulation will be reduced (Yan et al., 2022). In addition, the process of transferring dry matter from the nutritional organs such as stems and leaves to the grains is also critical, and this process is also affected by irrigation and nitrogen fertilizer application (Xue et al., 2006).

2.2 Impacts of irrigation frequency on biomass partitioning

The frequency of irrigation affects the distribution of dry matter in the wheat plant, such as to the stem, leaves, or ears. More frequent irrigation or more accurate timing of irrigation results in more dry matter being distributed to the ears and grains, which is important for increasing yield. For example, wheat that was irrigated four times during an important developmental stage had more total dry matter and more dry matter distributed to the ears than wheat that was irrigated only once or twice (Pal et al., 2000). When drip or sprinkler irrigation is used, more dry matter is distributed to the leaves and ears, and less to the stem and leaf sheaths, especially during the grain filling period. If water is insufficient, wheat will transfer previously stored nutrients to the grains to make up for the current loss of photosynthesis.

2.3 Developmental stage-specific responses

When to irrigate is also important, depending on the developmental stage of the wheat. Irrigation during the jointing, booting, flowering and filling stages can prolong the accumulation time of dry matter and allow more dry matter to be transferred to the grain (Ma et al., 2024). However, if there is a lack of water during the tillering stage or milky stage, the total amount of dry matter and the proportion transferred to the ear will decrease significantly, and the final yield will be greatly affected (Han et al., 2022). Supplemental irrigation from the booting stage to the filling stage can not only increase the dry matter in the nutritional organs and grains, but also reduce the dependence on pre-flowering reserves. Different irrigation times have different effects on wheat of different varieties and in different environments, which will affect yield and water use efficiency together (Moradi et al., 2022).

3 Water Use Efficiency (WUE) in Response to Irrigation Frequency

3.1 Definition and agronomic importance of WUE

Water use efficiency (WUE) of wheat refers to the amount of wheat yield or dry matter produced for each unit of water used. The higher the WUE, the more valuable the water is. This indicator is particularly important in water-scarce areas. Because water resources are scarce, improving WUE can help farmers save water while maintaining stable yields (Li et al., 2019b; You et al., 2022).

3.2 Effects of irrigation intervals on WUE

How to arrange irrigation and the frequency of irrigation will directly affect WUE. Appropriate irrigation time, such as irrigation at the jointing stage and heading stage, can make wheat grow well and reduce unnecessary water waste, thereby increasing yield and WUE at the same time (Si et al., 2020). For example, in semi-humid areas, if 60 mm of water is applied at the jointing stage and heading stage respectively, relatively high WUE and yield can be obtained (Bian et al., 2016). Increasing the number of irrigations but watering less each time, such as using drip irrigation or micro-spraying, can also improve WUE. This can keep the soil moist and photosynthesis more sustained. However, if irrigation is too frequent or too much water is used, it may waste water, which will reduce WUE and may not necessarily increase yield (Figure 1). In the case of water-saving planting, even if the total yield is slightly reduced, WUE may be higher. This shows that a good balance must be found between yield and water saving (Stallmann et al., 2020).

3.3 Factors influencing WUE dynamics

WUE is affected by many factors. For example, drip irrigation and micro-spraying combined with a reasonable irrigation frequency can improve WUE more than traditional irrigation methods, especially when water is insufficient (Hao et al., 2023). Soil type is also important. For example, loam or sandy soil, combined with a low precipitation environment, is more likely to achieve higher WUE under water-saving conditions (Yu et al., 2020). Different wheat varieties have different water use efficiencies. In addition, the effect of irrigation is different at different growth stages, such as jointing, booting or filling. Another method called "active water" or "oxygenated water" has also been found to improve WUE, especially when water is scarce (Wang et al., 2022). However, it should be noted that although increasing the irrigation frequency can improve WUE, using advanced irrigation systems also requires investment. In the end, it depends on whether it is worth it and whether a good balance can be found between increasing yield and saving water (Fang et al., 2018).

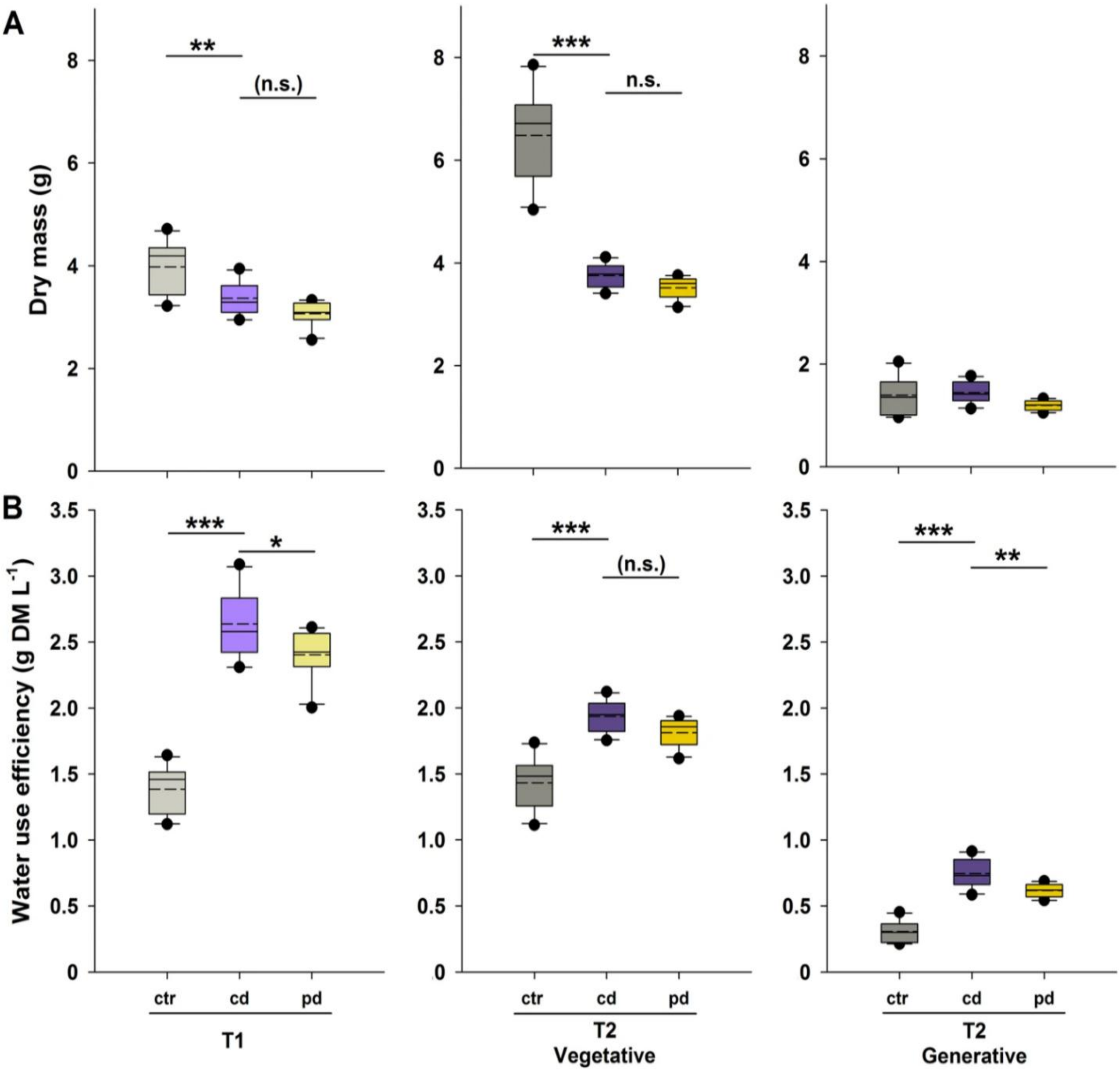

Figure 1 (A) Aboveground dry mass and (B) applied water use efficiency of wheat plants subjected to well-watering (ctr), continuous (cd) and pulsed (pd) drought, harvested at two time points (T1=77 d and T2=93 d after sowing). The applied water use efficiency was calculated for each pot as the ratio of aboveground plant dry mass to the cumulative amount of water received until harvest. At T2, values are given for vegetative (leaves and stems) and generative plant parts (ears). The boxes represent the interquartile ranges, whiskers extend to the 10% and 90% percentiles, respectively; solid lines show the medians, dashed lines the means. Outliers are shown as circles; when there was a significant effect of irrigation treatment, manual contrasts between selected groups were calculated and p values are given; ***$p<0.001$; **$p<0.01$; *$p<0.05$; (n.s.) marginally significant ($p<0.1$); n.s. not significant; n=10 (Adopted from Stallmann et al., 2020)

4 Mechanistic Insights and Physiological Responses

4.1 Root development and water uptake efficiency

Wheat roots are responsible for absorbing water and are a key part of water use. The role of the root system is particularly evident under different irrigation frequencies and drought conditions. Drought-tolerant wheat varieties usually grow thicker and larger roots. These roots can grow and absorb water better, and can also activate genes related to carbon metabolism and hormone signaling, thereby enhancing drought resistance (Hu et al., 2018). Root shape and structure, such as lateral root length and number of root tips, are directly related to water absorption efficiency. Using molybdenum fertilizer can make roots grow better, such as making roots more permeable to water, and can also increase the expression of water channel proteins, thereby enhancing water absorption capacity. The method and time of irrigation can also affect root distribution. If irrigation is more frequent, there will be more roots in the upper soil layer and the ability to absorb water will also be stronger (Jha et al., 2017). In addition, wheat with long root hairs and heavy root sheaths can also absorb water more easily and help control water evaporation.

4.2 Leaf morphology and transpiration

The coordination between leaves and roots also affects how water is used, especially during droughts or when there is little water. Sometimes wheat grows thinner roots to improve water absorption efficiency. Stable isotopes in leaves can be used to determine the current water status and transpiration rate of the plant (Brunel-Saldias et al., 2020). Studies have found that using molybdenum fertilizer can reduce leaf transpiration and allow roots to absorb more water, indicating that the direction of water flow has changed, and water is more concentrated in the roots for use rather than evaporating from the leaves (Wu et al., 2019). In addition, the relationship between some substances secreted by the roots and the surrounding microorganisms will also affect soil water retention, and these factors will also change the transpiration process (Rabbi et al., 2021).

4.3 Hormonal and molecular signals

Plants use hormones to regulate their response to water. One of the most important is abscisic acid (ABA). When the soil dries out, the roots sense it and produce ABA. This hormone travels to the leaves, closing the stomata, which reduces water loss and helps the plant save water during later droughts (Saradadevi et al., 2017). Drought-tolerant wheat generally has stronger protective mechanisms, such as stronger antioxidant capacity and more active hormones related to root growth (Hu et al., 2024). There is also a substance called nitric oxide, which is also involved in regulating root development and enhancing water absorption during drought, and these regulations may also be affected by the trace element molybdenum (Wu et al., 2019). From a molecular perspective, some transcriptome and metabolome studies have found that drought-tolerant wheat activates some special pathways, such as synthesizing flavonoids, osmoprotectants, and enhancing energy metabolism. These changes can help roots grow better and cope with drought.

5 Agronomic and Environmental Considerations

5.1 Yield stability under different irrigation schemes

Many studies have shown that wheat yield and water use efficiency (WUE) can be kept stable or even improved if irrigation time is chosen appropriately and water use is well controlled (Gao et al., 2022). This method will be even more effective if variety improvement is combined. Even in years with significant climate change, timely irrigation before sowing, during jointing or flowering can keep yields on track and reduce yield differences between years. In some places where water is scarce, appropriate reduction in water use (called "deficit irrigation") can increase WUE, and will have little impact on yield if soil conditions are suitable (Yu et al., 2020). In addition, combining scientific fertilization with water-saving irrigation can further improve yield stability and resource utilization efficiency (Huang et al., 2024).

5.2 Soil health and sustainability

To ensure sustained high wheat yields, the soil must be kept healthy. Reducing irrigation and applying fertilizers properly are effective methods. For example, controlling the amount of water and combining it with appropriate nitrogen fertilizers can make the soil healthier, reduce nitrogen loss, and reduce pollution to the environment (Xu et al., 2020). Long-term use of organic fertilizers plus some inorganic fertilizers can not only increase yields, but also make yields more stable and less likely to fluctuate too much (Han et al., 2020). Conservation tillage measures such as returning straw to the field and no-till farming can also make the soil softer, better at retaining water, and more organic matter, which is very helpful for future farming (Li et al., 2023).

5.3 Economic and practical aspects

Water-saving methods such as drip irrigation and sprinkler irrigation, if combined with nitrogen fertilizer application, can grow more wheat with less water and fertilizer. This method not only improves yield and input efficiency, but also saves costs and reduces pressure on the environment (Yuan et al., 2022). In many cases, even if a little water and fertilizer are reduced, the yield may drop slightly, but the saved input is enough to make up for these losses, and the farmer's income is still not affected (Qu et al., 2025). A practical suggestion is to arrange irrigation time according to local rainfall and soil conditions, and add some organic amendments, such as farmyard manure, when necessary, to improve yield and soil fertility (Verma et al., 2023). These practices can take into account both making money and protecting the environment, so farmers are naturally willing to adopt them.

6 Case Study: Irrigation Frequency Effects in a Semi-Arid Wheat-Growing Region

6.1 Study region and climatic characteristics

Places like the North China Plain, Pakistan's Sindh Province, and southern Egypt are typical semi-arid wheat-growing areas. These places have several characteristics: little and unstable rainfall, hot weather, rapid evaporation, and perennial water shortages. In such an environment, if you want to grow wheat well, you must use water carefully to maintain yields and improve water efficiency.

6.2 Experiment setup and findings

Many field trials and model studies have done this kind of test to see how different irrigation methods affect wheat yield and WUE. In a study in Pakistan, some people tried to reduce the amount of irrigation by 40% to 50%. The results showed that although the yield decreased slightly, the water use efficiency was higher. For example, with half the amount of water, wheat yield can still reach 1 925 kg/ha and WUE reached 4.47 kg/m^3-4.57 kg/m^3 (Figure 2); while full irrigation uses more water but is less efficient (Jabeen et al., 2021). A four-year experiment was also conducted in the North China Plain. Irrigation was carried out in four stages: greening, jointing, flowering and filling, with a total of 240 mm of water. The result was a yield of 7 909 kg/ha and a WUE of 33 kg/ha/mm, the highest. If more water was applied, the yield did not change, but the WUE decreased (You et al., 2022). Research in Sindh Province found that reducing irrigation at different stages had different effects. If water is stopped during the tillering stage, the yield will drop significantly, up to 17%; but if irrigation is reduced during the grain maturity stage, the yield can still be maintained at 98.5%, and WUE will increase. This shows that the tillering stage is most sensitive to water shortage (Memon et al., 2021). In Upper Egypt, drip irrigation was used at 75% of the water requirement, and the WUE of wheat increased by 59% and the grain yield increased by 20%. This shows that in water-scarce areas, controlling the amount of irrigation can also improve water use efficiency and yield (Eissa et al., 2018).

6.3 Implications and recommendations

Studies have shown that in some stages that are relatively less afraid of water shortage, such as grain maturity, less water can be used, which can not only maintain yield but also increase WUE. However, in critical stages such as tillering, water cannot be less, otherwise it is easy to reduce yield. We recommend that irrigation be arranged during important growth stages of wheat, such as greening, jointing, flowering and filling. At the same time, attention should be paid to controlling the total water consumption, such as about 240 mm, so that both yield and water saving can be taken into account. In order to better manage water, farmers are also advised to strengthen soil moisture monitoring. In addition, drip irrigation and other water-saving irrigation methods are also worth promoting. These methods are particularly suitable for water-scarce areas and can greatly improve water use efficiency.

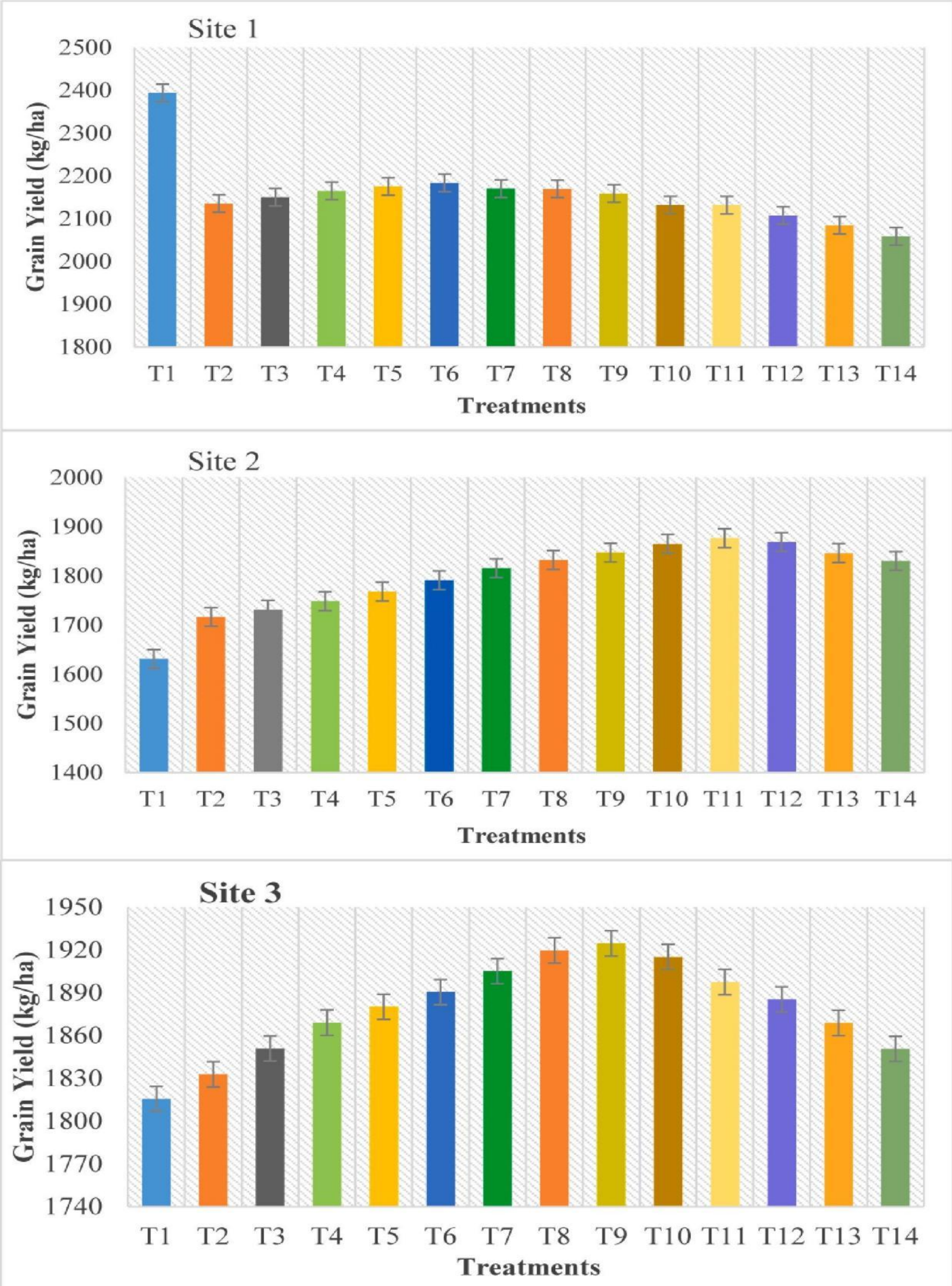

Figure 2 Effects of deficit irrigation on grain yield of wheat. T1=255 mm; T2=242 mm; T3=229 mm; T4=217 mm; T5=204 mm; T6=191 mm; T7=178 mm; T8=166 mm; T9=153 mm; T10=140 mm; T11=128 mm; T12=115 mm; T13=102 mm; T14=89 mm (Adopted from Jabeen et al., 2021)

7.2 Integration with precision agriculture tools

There are many precision agriculture tools available today, such as remote sensing, soil moisture sensors, and connected smart irrigation systems. These can help farmers better determine when and how much water to use. This saves water while ensuring that wheat grows well (Finco et al., 2023). If these technologies are combined with genetic breeding, biotechnology, and agronomic measures, wheat will perform better in terms of drought resistance, water conservation, and sustainability (Xing and Wang, 2024). However, we still need to do more research to see whether these technologies can really be implemented in different regions, whether farmers are willing to use them, and whether the effects are good in the long run.

7.3 Climate change and policy implications

Future climate may bring more problems, such as reduced rainfall, higher temperatures, and tighter water resources, which will affect the irrigation needs of wheat (Li et al., 2019a). However, studies have also found that even if the climate continues to deteriorate, as long as reasonable irrigation methods are adopted, such as climate-smart irrigation or moderately less irrigation, high yields can still be maintained while saving water (Gao et al., 2024). This also shows that policies are very important. The government should encourage farmers to use more efficient irrigation methods, such as irrigating only when the soil moisture drops to a certain value. It is also necessary to promote more precision agriculture technology to help farmers achieve water conservation goals (Mehmood et al., 2023). At the same time, policies should also consider the possible impacts of future climate change. We cannot only look at the present, but also formulate response plans that can ensure food security and take care of the environment in the long term (Zaveri and Lobell, 2019).

8 Concluding Remarks

Choosing the right number of irrigations and the amount of water to use each time is particularly important for improving wheat yield and water use efficiency (WUE). Generally speaking, 240 to 315 mm of water during the key growth period can achieve high wheat yields and good WUE. If you water too much, it will not be beneficial. Not only will it waste water, but it may also wash away nutrients. In places with little rainfall and suitable soil, it is a good idea to irrigate less water appropriately (also called deficit irrigation). This will not only increase WUE, but also prevent yields from dropping too much. The relationship between yield and WUE depends mainly on when to irrigate, how to irrigate, and what the environment is like. If you can coordinate irrigation with fertilization, you can further increase yield and WUE, while reducing fertilizer loss, which is good for the environment and can help farmers save money.

In arid or semi-arid areas, it is recommended to irrigate 60 mm of water at each stage during the greening period, jointing period, flowering period, and filling period, for a total of 240 mm, which works well. You can also irrigate less water at each growth stage, such as 25% less than full irrigation. This method can save water, improve WUE, and basically not reduce yield, especially in sandy loam. In addition to controlling the irrigation time and amount of water, the amount of fertilizer should also be matched. For example, applying 250 kg of nitrogen fertilizer per hectare can increase the yield, WUE and economic benefits, while also reducing environmental pollution. Using water-saving equipment such as drip irrigation or sprinkler irrigation, combined with tools such as the crop water stress index (CWSI) to monitor crop status, can also help farmers better decide when and how much to water.

In short, in water-scarce areas, if you want to grow wheat well, produce more, and not affect the environment, you have to use scientific methods to irrigate and fertilize. As long as the right method is used, farmers can save water and money, ensure income, cope with climate change, and maintain food security.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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