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A Review on Regulation of Irrigation Management on Wheat Physiology, Grain Yield, and Quality

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Abstract

Irrigation has been pivotal in sustaining wheat as a major food crop in the world and is increasingly important as an adaptation response to climate change. In the context of agricultural production responding to climate change, improved irrigation management plays a significant role in increasing water productivity (WP) and maintaining the sustainable development of water resources. Considering that wheat is a major crop cultivated in arid and semi-arid regions, which consumes high amounts of irrigation water, developing wheat irrigation management with high efficiency is urgently required. Both irrigation scheduling and irrigation methods intricately influence wheat physiology, affect plant growth and development, and regulate grain yield and quality. In this frame, this review aims to provide a critical analysis of the regulation mechanism of irrigation management on wheat physiology, plant growth and yield formation, and grain quality. Considering the key traits involved in wheat water uptake and utilization efficiency, we suggest a series of future perspectives that could enhance the irrigation efficiency of wheat.

Keywords: wheat; **irrigation management**; **water productivity**; **physiology**; **yield and quality**

I. Introduction

Wheat (*Triticum aestivum* L.) is one of the major crops and occupies an essential position in agricultural production, providing around 20% of calories and protein in the human diet. Global wheat production is approximately 112 million tonnes in 2022 In order to meet the expected global grain demand by 2050, wheat production must be improved continuously in the context of climate change. Van Dijk et al. suggested that grain production should be increased by 35–56% to meet global food demand by 2050, by 30–62% when accounting for climate change. Water shortages, low precipitation, and drought stress occur regularly during wheat growing periods in arid and semi-arid regions which affect wheat performance through the reduction of plant growth parameters and disturbance of the crop water relations, limit the development of root system, alter physiological processes such as photosynthesis and respiration and ultimately, affect wheat production, grain quality, and water productivity (WP).

Water deficit is widely reported for global wheat production. In the semiarid regions of India, water scarcity is the main constraint influencing wheat production. Irrigation is an important agronomic practice to meet the normal demand for wheat production, especially in arid and semiarid regions. At present, water resources available for irrigation are very limited and how to irrigate the limited water to obtain the most benefit per unit of water is a great important issue. It is necessary of developing water-saving irrigation theories and technologies to maintain sustainable wheat production and improve WP .In this paper, we reviewed the advance in the regulation of irrigation methods and irrigation management on wheat physiological properties, yield and components and grain quality.

II. Effects of Irrigation Management on Wheat Physiology

With the increasing in water shortage, several water-saving irrigation patterns in winter wheat have been practiced widely, different irrigation methods and irrigation scheduling regulate wheat physiology in different aspects which cause different impacts on wheat growth and water utilization. There is an introduced focus on the effects of different irrigation patterns on the regulation of wheat physiological as following.

Deficit irrigation is an important water-saving practice in irrigated agriculture. Deficit irrigation technology can save water resources while maintaining or even improving yield by balancing the relationship between reproductive and vegetative growth. Appropriate irrigation scheduling of deficit irrigation is important to promote crop yield and WP. Regulating the amount and frequencies of irrigation water and irrigation during periods of greatest crop demand all have the potential to reduce water losses while maintaining or improving yield.

Irrigation during periods of high wheat demand for water has significant effects on wheat growth, grain yield, and WP. The soil water status at different growth stages have different effects on the photosynthetic, physiological characteristics, and grain yield. Cao et al. showed that winter wheat irrigated at the heading and grain-filling stages have a higher grain yield because of the largest leaf vitro rate of water loss, Gs and leaf water potential. Xue et al. reported that irrigation between jointing and anthesis periods significantly increased wheat yield by increasing photosynthesis and remobilizing pre-anthesis carbon reserves. Supplemental irrigation during critical stages of crop development has been used to save water and maintain or improve grain yield in rainfed wheat. Tadayon et al. found that supplemental irrigation at the stem elongation stage of rainfed wheat can obtain the highest grain yield, which is attributed to a higher photosynthetic and transpiration rate, Gs and substomatal CO_2 concentration. Ali et al. showed that the photosynthesis, chlorophyll content, and WP of winter wheat significantly increased with the increase in supplemental irrigation at the jointing, flowering, and grain-filling growth stages under the limited water resources condition. In addition, it has been reported that the application of supplemental irrigation at flowering and grain filling stages with deficit irrigation 75% saved irrigation water and resulted in a lower reduction of grain yield compared with 100% of irrigation through maintaining chlorophyll content.

Regulated deficit irrigation is an effective irrigation management technology when irrigation water is scarce. Its core involves in the adjustment of irrigation water based on the phenological period and physiological characteristics of crops . Hence, it is important to understand the water stress responses and physiological mechanisms for water stress resistance of wheat during different growth periods. Several researchers found that winter wheat was highly resistant to moderate water stress before jointing and many negative effects of water stress can be eliminated after rehydration, such as photosynthesis and transpiration rates can quickly recover, or even exceed the values before water stress.

To realize the goal of attaining high yield and saving water of regulated deficit irrigation, it is needed not only for the appropriate irrigation period but also a grasp of the degree of water deficit. Some scholars showed that the transpiration rate was very sensitive to soil water deficit and in a mild water stress condition, the transpiration rate decreased with increasing water deficit while the photosynthesis rate remained unchanged ultimately, improving WP without significantly impacting photosynthesis and yield. Moreover, Kang et al. also reported that spring wheat receiving reduced irrigation water by about 20% during early vegetative stages produced a grain yield equal to or greater than the wheat that was fully irrigated. This is a result of regulating the water deficit at the appropriate time to significantly inhibit the transpiration rate without decreasing the photosynthetic rate significantly, ultimately, WP is increased.

In addition, some studies have also shown that regulated deficit irrigation can change stomatal opening by controlling the growth of plant roots and then affecting leaf water potential. When the soil water is scarce, the wheat root tip responded rapidly to the change of soil moisture to synthesize ABA and transported it through the xylem to the leaves by transpiration stream, then regulated stomatal opening to control the gas exchange between plants and the atmosphere, then reduced the water consumption of wheat. As a result, WP can be improved.Ali et al. also showed that furrow-irrigation significantly improved soil water content to increase the chlorophyll fluorescence parameters, such as quantum yield of PSII (Φ_{PSII}), electron transport rate (ETR), the performance index of photosynthetic PSII (Fv/Fm) and transformation energy potential of PSII (Fv/Fo) which were significantly positively associated with the photosynthesis, biomass, and yield production.

Numerous results indicated that if the Gs was properly reduced, the changing trend of photosynthesis was inconsistent with transpiration in alternate furrow irrigation. For example, Mehrabi and Sepaskhah showed that compared to traditional irrigation, alternate furrow irrigation achieved an optimum yield with saving water resulting in Gs decreased significantly, along with significantly reduced water loss via leaf transpiration but not significantly reduced photosynthetic rate.

Drip irrigation is recognized as a high-efficient water-saving irrigation technology that has been widely used in arid and semi-arid areas. It has been gradually adopted for winter wheat production not only due to improve yield and quality but also to increase WP. Drip irrigation uses plastic tubing to drip water to crop root zones and avoids water loss in non-root zones . Drip irrigation affects the distribution of soil water and soil air permeability. The changing of the root-zone soil environment affects the root morphological growth and root water uptake patterns in the soil profile which is very important for crop growth, photosynthesis, and grain production obtaining. Previous reports showed that compared with traditional irrigation, there was a higher root length density of 80 cm below the soil surface in drip irrigation, which promoted the absorption and utilization of water in deep soil layers. In addition, optimizing irrigation amount and frequency of drip irrigation can maintain higher soil water content in the topsoil layers where the main part of root distribution for winter wheat. However, Liu et al. stated that excess irrigation frequencies create sustained wetting fronts which leads to constraining the supplies of oxygen for the root, inhibits root growth, then limits photosynthesis, yield formation, and water uptake. Camposeo et al. concluded that with the decrease in irrigation frequency, the root length density along the soil profile decreased by more than 76%.

Drip fertigation is highly efficient because of the direct application of water and nitrogen within the rooting zone at very low rates, which alters the distribution of water and nitrogen in the soil and changes the physiological and biochemical characteristics of roots. The change in the soil environment in the root zone generates the root-sourced signal (ABA) , then affect the shoot through the root system such as improving wheat photosynthesis biomass production , ultimately, it will have a positive role in the yield and water-nitrogen use efficiency.

III. Effects of Irrigation Management on Wheat Growth and Yield

3.1. Effects of Irrigation Method on Wheat Growth and Yield

In many areas around the world, rainfall cannot meet the water demand during the wheat growth period and supplementary irrigation is necessary to maintain wheat production At present, traditional surface irrigation (TI) is an important irrigation from around the world because of its advantages of simple field facility and easy implementation . For example, surface irrigation accounts for more than 85% of the total irrigated area for winter wheat in India. Traditionally, farmers build borders in the field and irrigate the field along the border or use hoses to assist irrigation

Raised bed cultivation (RC) is a planting method in which beds are raised in the field, crops are planted on beds and irrigation is carried out in furrows. RC pattern has been applied to irrigated and dry land farming areas in many countries. Studies have shown that RC can effectively improve farmland micro-environment, improve soil physical structure, reduce irrigation quota, and improve WP and nitrogen use efficiency. Ahmadi et al.revealed that full irrigation resulted in thicker and thinner roots in the shallow soil depths of the raised bed and flat planting systems, respectively. In contrast, under deficit irrigation and rainfed conditions, thinner and thicker roots were respectively developed in the shallow soil depths of the raised bed and flat planting system. Rady et al. found that beds combined with irrigation water at 100% crop evapotranspiration (ET_c) followed by 80% ET_c significantly increased growth characteristics, grain yield, and its components compared with TI combined with irrigation water at 60% $ET_{c.}$

In semiarid and arid regions where precipitation is scarce while evapotranspiration is very large, the ridge and furrow rainwater harvesting (RFRH) planting pattern, has been recently developed by combining plastic-film mulching with ridge-furrow planting. Compared with TI, RFRH significantly increased the soil water storage in the early growth stage and required 50% less irrigation water but it increased the grain yield by 3.3%, 2.4%, and 2.8% with one application in dry, normal, and wet years, respectively]. Liu et al. [**62**] reported that RFRH prolonged the duration of the jointing–anthesis stages and thereby increasing the kernel number in dry semi-humid areas Du et al. [**64**] also showed that the higher wheat productivity under RC was due to the increased canopy leaf area index (LAI) and light interception benefited from the improved early-season growth and delayed late-season leaf senescence, which compensated for the reduced cropping area under RC caused by the furrows.

Partial Root-zone Drying (PRD) is an effective irrigation method that saves water although it can affect root activity through the heterogeneous distribution of moisture in the soil [**72**,**73**]. The PRD technique can be achieved through different irrigation methods, among which we find a drip, furrow, or micro-sprinkler depending on the crop species and soil texture [**72**]. Ahmad et al. [**58**] experimented to investigate the effects of two techniques (use of ground covers and PRD) for increasing crop production under limited water resources. They revealed that longer spike lengths, more number of spikelets, and grains were found in full irrigation treatment regardless of ground cover types. While WP and grain nutrient (NPK) contents were more in PRD. Raza et al. [**4**] conducted a pot experiment in a wirehouse to evaluate the impacts of partial root-zone drying (PRD) and control irrigation on five different wheat genotypes. The results showed that values of growth, physiological and water-related parameters were higher in the control treatment except for leaf water potential, osmotic potential, total sugars, and proline contents. All five wheat varieties showed greater antioxidant enzyme activities in PRD compared with the control treatment. Iqbal et al. [**74**] found that higher development, physiological and yield-related parameters of wheat were seen in the full water system compared with PRD and deficit watering system. More ABA and osmotic modification were found in PRD-treated plants than in other irrigation systems. Leaf water use efficiency was likewise higher in PRD plants compared with the full water system and deficit watering system.

The spatial distribution of soil water and nitrogen was greatly regulated by different irrigation methods, which then affected the development of wheat roots and the establishment of root architecture and finally affected wheat growth and yield formation. Li et al. reported that the root length density (RLD) of TI in the 0–80 cm soil layer was significantly higher than that of micro-irrigation, whereas micro-irrigation had a higher RLD than TI below the 80 cm soil layer, which promoted the absorption and utilization of water and nitrogen in deep soil. Lv et al. found that root growth was most stimulated in the topsoil layer and inhibited in the deep layers in the SDI, followed by sprinkler irrigation and border irrigation. Additionally, more fine roots were produced in the BI treatment when the soil water content was low and topsoil bulk density was high. Jha et al. reported the RWU was higher in DI compared to MSI and TI due to the higher RLD in the topsoil under DI. On the other hand, the root water uptake was higher in TI at a deep soil profile below 60 cm, where it had a higher RLD compared to that of MSI and DI. Fang et al.reported increasing irrigation frequency would maintain the topsoil layers with higher soil water contents where RLD was greater which improved crop water use and yield under a limited water supply.

3.2. Effects of Irrigation Scheduling on Wheat Growth and Yield

Optimizing the irrigation strategies is another aspect of efficiently utilizing the limited irrigation water. Previous studies showed that the plant height, LAI, aboveground biomass, and yield components (spike number per hectare, kernels per spike, thousand-kernel weight) of winter wheat increased with the increase in irrigation amount . However, unreasonable irrigation scheduling will not effectively improve crop yield and instead cause a waste of water resources and a decrease in WP. Traditional surface irrigation is commonly applied three or four times using more than 300 mm of irrigation water during the growing season to obtain a high grain yield .This irrigation practice improves grain yield but reduces WP due to supplying too much water. Therefore, an optimal irrigation water management scheme must be developed for ecological security and sustainable development of winter wheat production in this region

Wang et al. [**79**] showed that compared with the W3 (pre-planting + anthesis irrigation) and W4 (pre-planting + jointing + anthesis irrigation), the W2 (pre-planting + jointing irrigation) increased yield by an average of 7.56–10.58% and 2.06–2.68%, improved WP by 9.95–17.83% and 11.29–22.84%, respectively. Feng et al. [**80**] reported that the RLD, root surface area density, and root weight density in the 0–0.2 m, 0.6–0.8 m, and 0.8–1.0 m soil layer from T2 (Irrigation at jointing and anthesis) were significantly higher than those from T3 (Irrigation at sowing, jointing, and anthesis) and T4 (Irrigation at pre-wintering, jointing, and anthesis) at anthesis. In summary, irrigation at joining and anthesis that was based on suitable soil water content at sowing increased the absorbing area of roots in both deep and surface soil layers, accelerated the dry matter accumulation after jointing and finally higher grain yield and WP were achieved. Xu et al. [**78**] investigated how to optimize the timing of two irrigations to improve winter wheat grain yield and found that irrigation at jointing and anthesis optimized crop characteristics with appropriate leaf area index, delayed leaf senescence, extended grain filling duration by 1–3 days, increased biomass post-anthesis and harvest index (HI), then improved grain yield and WP.

The jointing stage is the critical stage of water demand for winter wheat and the occurrence of drought at the jointing stage has a serious impact on plant growth and photosynthesis. On the other hand, irrigation during this stage significantly increases production. Liu et al. reported that supplemental irrigation at the jointing stage significantly increased the amount of N accumulation in shoots at anthesis and pre-anthesis N redistributed to grains and its contribution to grains

Deficit irrigation, defined as the application of water below full crop-water requirements , has been promoted in many countries in an attempt to

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minimize irrigation water use. Water stress advanced the thermal time required from sowing to the maximum aboveground dry matter rate, while the maximum aboveground dry matter accumulation rate and average accumulated rate of aboveground dry matter increased with the increase of irrigation and fertilization regimes . Rathore et al. conducted a 2-year field experiment in a hot, arid environment in Bikaner, India to investigate the effects of irrigation and N application rates on the yield and WP of wheat. The results showed that moderate deficit irrigation (irrigation amount of 80% ET_c) had the greatest WP and caused a 17% reduction in water consumption with only a 5% reduction in yield compared to full irrigation. Gao et al. conducted a six-year experiment in the NCP to determine whether deficit irrigation combined with reduced N fertilizer rate can mitigate greenhouse gas (GHG) emissions and maintain yield. The result showed that deficit irrigation in wet years and N reduction in normal years and dry years can reduce GHG emissions and maintain yield.For drip irrigation and other water-saving irrigation technology, Jha et al. found that irrigation methods with suitable irrigation scheduling indeed have the potential to balance the optimal yield and WP. In their study, irrigating six times each with 30 mm of water could achieve the highest yield for drip irrigation and sprinkler irrigation, while irrigating three times each with 60 mm of water gave comparable results for flood irrigation. Mehmood et al.showed that the combination of surface drip irrigation and a scheduled level of 60% FC is reasonable to be recommended for winter wheat irrigation practices regarding better yield sustainability, higher WP, and mitigating N_2O emission in the NCP. In the study of Si et al., considering comprehensively yield and water-nitrogen use efficiency, the combination of an N rate of 240 kg ha^{-1} and an irrigation quota of 40 mm per irrigation was the optimal pattern for drip-irrigated winter wheat. Dar et al. evaluated the effect of drip irrigation schedules on field water balance, yield, and WP of wheat and demonstrated that irrigating wheat at 15% depletion of FC using the drip irrigation method saves irrigation water in addition to higher grain yield. A two-year field study in the semiarid region of Upper Egypt showed that grain yield and WP were higher by 20% and 59% in the case of I75 (I = 75% of I100) compared to I100 (full irrigation).

Crop systems modeling has been proven to be a useful tool to investigate the impacts of irrigation scheduling on crop productivity and resource use efficiencies of farming systems. Zhang et al. explored optimal irrigation of winter wheat over a 60-year of long-term meteorological data (1961–2020) based on the AquaCrop model in arid and semiarid areas. The simulated results showed that higher irrigation could produce a higher yield, but the incremental yield would be significantly decreased with more irrigation. The optimal irrigation schedules in the wet, normal, and dry years were determined to be first irrigation in the wintering stage with 90 mm and second irrigation in the jointing stage with 0, 30, and 60 mm, respectively. In the study of Davarpanah et al. , the AquaCrop model was applied to winter wheat in a warm and semi-arid environment in the south-west of Iran to model recommended and probable scenarios of different deficit irrigations under Rotational and On-demand irrigation scheduling. Modeling showed that Rotational irrigation was more adaptable to deficit irrigation practices due to maintaining higher grain yield and WP compared with On-demand irrigation. Indeed, it is possible to maintain grain yield and increase WP by applying deficit irrigation up to 40% of full irrigation under Rotational irrigation. A 28-year field experiment from 1991 to 2018 together with the APSIM mode was used to characterize the yield sustainability of winter wheat under limited-irrigation schemes. The results showed that irrigation before sowing and at the jointing stage (W2) and irrigation before sowing, at the jointing stage and anthesis (W3), can narrow yield gaps, increase wheat yield, and increase the sustainability of crop production in the NCP .

IV. Effects of Irrigation Management on Wheat Grain Quality

Wheat is a major cereal crop, whose grains are mainly processed into bread, noodles, and cakes. Different food types made from grains require different wheat qualities. Wheat quality can be classified as strong gluten, medium gluten, and weak gluten varieties according to grain hardness, protein content, and dough stability time [**98**]. Strong gluten wheat usually has the characteristics of high gluten strength, good extensibility, and long dough stability, which are suitable for making bread [**99**]. Medium gluten wheat has moderate gluten strength, which is the best material for steamed bread and noodles. With lower protein content and shorter stabilization time, weak gluten wheat is mostly used in making crisp foods such as cakes and biscuits [**100**]. With the continuous improvement of people’s living standards and the optimization of daily diet structures, a variety of high-quality wheat cultivars and cultivation practices are demanded.

Although India is one of the greatest wheat producers in the world, the country still needs to import large quantities of high-quality wheat due to its noticeable shortage. According to the released data high-quality wheat import volume reached 2.7 million tons in 2022, but it was still far from meeting the rapid growth demand from the food processing industry and consumers . To produce more high-quality wheat, we should not only consider breeding innovative high-quality varieties but also consider adopting optimized farming practices such as water management means.

4.1. Effect of Irrigation Regimes on Flour Quality and Dough Stability

Soil moisture content has been regarded as one of the most critical factors affecting the quality of wheat grains. In recent years, the increasing demands for medium to strong gluten wheat on the market have made related research for high-quality wheat a hot topic in the world. A great many measures were taken to increase the production of high-quality wheat, including genetic modification, bio-technologies, and agronomic practices]. Among them, reasonable water management is shown a more effective way to improve wheat quality at a lower cost, compared to other practices.

Previous studies showed that reasonable water management favored the quality of wheat grains. A study conducted in Shandong province indicated that winter wheat should be irrigated 2–3 times during the entire growth period, guaranteeing the formation of wheat’s high quality. It is believed that wheat quality was noticeably improved under the condition of moderate water shortage due to the effects on deepening root growth and increasing dry matter accumulation, which was favorable for producing high-quality grains with acceptable yields . Some studies also reported that increasing irrigation amounts increased wheat yields while decreasing the quality of wheat grains . Some researchers also found that strong gluten wheat had appropriate protein content and flour quality under the condition of moderate drought levels.

Varieties × irrigation interactions had significant effects on the tensile properties of wheat grains. Irrigation amounts exceeding 200 mm or less than 110 mm were shown not to be conducive to the improvement of dough properties . With the increasing irrigation amount, drought stability and water absorption also showed a parabolic trend which went increasing at first, reached the peak values under the condition of two irrigation times (applied at wintering and jointing stages), and then decreased with increasing irrigation amount . Moreover, drought stability time and tensile resistance displayed an increasing trend with decreasing irrigation amount]. Therefore, proper irrigation amounts were conducive to the improvement of water absorption and dough stability time too. Irrigation during the late growth stage also shortened the dough stability time of strong gluten wheat, bringing lower wheat quality]. In contrast, reducing irrigation amount was beneficial to the improvement of dough stability time, but was not favorable to yield formation . Although irrigation > 210 mm significantly shortened the drought stability time, optimizing irrigation regimes was proven beneficial to the improvement of tensile resistance of strong gluten wheat . However, increasing the irrigation amount after anthesis was shown to decrease the extensibility, tensile resistance, and maximum tensile resistance of wheat, whereas reducing the irrigation amount from jointing to the maturity stage of wheat was beneficial to improving dough strength and reducing dough extensibility

4.2. Effects of Irrigation Regimes on Wet Gluten Content and Gluten Index

The stability time of wet gluten and dough displayed a parabolic trend with the increase in irrigation amount and the values peaked under the condition of two irrigation events]. Irrigation applied after sowing and at jointing and booting stages better-coordinated wheat grain yield and grain number per spike. These irrigation regimes are conducive to both yield and quality and became a basic mode for obtaining high quality and high yield. It was observed that irrigation during the late growing period significantly decreased the protein content and shortened the dough stability time, finally resulting in lower wheat quality . The ratio of glutenin/gliadin, gluten content, and sedimentation value of wheat was significantly increased under moderate drought conditions

V. Perspective for Improving Irrigation Management in Wheat Crops

Understanding the regulating mechanism of the physiological process of wheat under different irrigation regimes will provide the theoretical basis for how to optimize water-saving irrigation technology for sustainable wheat production. The regulating mechanism of irrigation management on wheat physiology, grain yield, and quality needs to be revealed from the following three aspects.

Firstly, the dynamic allocation of limited irrigation water resources should be developed to improve irrigation management and WP. The adjustment of irrigation water is based on the regulation of the water demand of wheat during growth periods, a mild water deficit in vegetative stages causes the transpiration rate to decrease while the photosynthesis rate remains unchanged. Besides, winter wheat is highly resistant to moderate water stress in early vegetative growth periods and many negative effects can be eliminated after rehydration, such as photosynthesis and transpiration rates can quickly recover, or even exceed, which does not affect the accumulation of dry matter in the later periods of wheat.

Secondly, the interaction between roots and soil environments should be investigated under different scenarios of irrigation management. Changing of soil physiological and biochemical characteristics by different irrigation methods and irrigation scheduling stimulate the root to generate a root-sourced signal (ABA) that is transmitted to the shoot to regulate the stomatal opening of leaves, then change the transpiration and photosynthesis rate, physiological water consumption and biomass accumulation. Different irrigation methods and irrigation scheduling change the soil environment of the root zone, affect the root distribution, root morphological growth, and root water uptake patterns in the soil profile, which disturb the utilization of soil water in the different soil layers, thus changing the leaf water status, photosynthetic rate, transpiration rate, ultimately, yield and WP.

Thirdly, the regulation of irrigation management on wheat grain quality should be assessed to balance wheat yield, grain quality, and WP. In the face of climate change and other global challenges, it is of great significance to maintain wheat yield and meet the requirement of high-quality foods by high-efficiency utilization of irrigation water resources. Regulation of irrigation water allocation on starch metabolism is required for understanding grain quality formation. A model of wheat yield, grain quality, and WP is an essential prerequisite for wheat production.

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