Optimizing Water Use Efficiency and Yield of Wheat Crops Through Integrated Irrigation and Nitrogen Management: A Comprehensive Review

Abstract

Achieving sustainable agricultural productivity is critical due to the rising worldwide demand for food and the growing scarcity of water.This comprehensive review investigates the complex interrelations where integrated irrigation and nitrogen management are used as a strategic method to improve wheat crop yields and water use efficiency (WUE).The study synthesizes current research findings, methodologies, and technological advancements related to optimizing water and nitrogen inputs in wheat cultivation. A number of factors can affect WUE in wheat, including climate, soil, crop management practices, and genetic factors. There are a number of irrigation and nitrogen management practices that can be used to improve WUE in wheat, including deficit irrigation, mulching, and split applications of nitrogen fertilizer. The review underscores the significance of tailored irrigation and nitrogen management strategies in mitigating water stress, reducing nutrient runoff, and promoting sustainable agricultural practices. Insights from this comprehensive analysis aim to guide policymakers, agronomists, and farmers in making informed decisions for optimizing wheat production while conserving water resources and minimizing environmental impact. Future research on WUE can help to ensure that wheat production remains sustainable in the face of future challenges such as climate change and water scarcity.

Keywords: Water use efficiency, Wheat, Integrated irrigation, nitrogen management, Sustainable agriculture, Yield optimization.

Introduction

Wheat(Triticum species), a vital crop essential for global sustenance, traces its origins to the Central Asian region, boasting a staggering worldwide production of 750 million tons. Within this global landscape, India plays a significant role, contributing 13% with a production volume of 109.52 million tons (Singh et al., 2013). Over the past 75 years, wheat production in India has witnessed substantial growth, particularly in the aftermath of the Green Revolution. However, despite this progress, the agricultural sector faces persistent challenges, including plateauing yield potential, diminishing irrigation water availability, inadequate access to quality seeds, low seed replacement rates, the stress of climate change, imbalanced fertilizer usage, and existing yield gaps at the farm level.

In the current scenario, agriculture confronts unparalleled challenges due to climate change and the depletion of natural resources. In India, where agriculture stands as the primary consumer of water, over 75% of the nation's freshwater resources are allocated to agricultural purposes (Shekhar, 2022; Khose et al., 2022). The increasing demand from other sectors intensifies competition for water resources, necessitating the agricultural sector to enhance productivity with reduced water usage. A pivotal challenge faced by researchers is the imperative to augment food production per unit of water. The looming threat of water scarcity, stemming from factors such as excessive water consumption, declining groundwater levels, soil salinization, and pollution, poses a grave risk to the sustainability of agricultural production (Li et al., 2004; Wang et al., 2012). In this complex landscape, the need for innovative solutions and sustainable practices is more pressing than ever to ensure the resilience of global wheat production.

Water and nutrients are essential inputs for crop production and should be applied in adequate amounts during the crop season for proper growth and optimum yield (Shekhar et al., 2018; Shekhar et al., 2019; Balasaheb and Biswal, 2020; Bhausaheb et al., 2021). Water plays a crucial role in nutrient uptake (Aliasgharzad et al., 2006; Shekhar et al., 2017; Shekhar et al., 2020) and influences most plant physiological processes such as photosynthesis, photosynthetic materials transmission to seeds, cell development, and transmission of nutrients in plants (Shekhar et al., 2020; Shekhar et al., 2021a). The deficiency of water creates unfavorableconditions for nutrient uptake and plants experience stress (Shekhar et al., 2020; Shekhar et al., 2021b; Shekhar et al., 2021c; Shekhar et al., 2023). In many parts of the world, water shortage is an important limiting factor in grain (Dong et al., 2011; Araya et al., 2019). Water stress affects the crop's ability to absorb nutrients from the soil, especially nitrogen.

In the agricultural landscape of India, urea stands out as the predominant fertilizer (FAO, 2011; Shekhar et al., 2021b). Nitrogen, a crucial and highly volatile nutrient in the soil, is subject to intricate dynamics, as highlighted by Shekhar et al., (2021b). The volatility of nitrogen renders it most accessible to plants in well-moistened soil, a condition typically maintained through effective irrigation practices.

However, the challenges associated with nitrogen management are multifaceted. Excessive irrigation and heavy rainfall have the potential to transport nitrate beyond the root zone, posing a risk of groundwater pollution. Conversely, inadequate watering can lead to the production of ammonia, which may evaporate into the surrounding air. Striking the right balance in irrigation practices is pivotal not only for mitigating these risks but also for optimizing plant conditions conducive to enhanced photosynthesis and efficient uptake of water and nutrients. Achieving this delicate equilibrium is essential to foster plant growth and ensure the judicious use of fertilizers in the pursuit of sustainable agricultural practices.

2. Water Use Efficiency and Transpiration Efficiency

Water-use efficiency (WUE) is expressed as the ratio of total biomass to evapotranspiration or as the ratio of grain yield to water received from irrigation and rain (Qui and Wang, 2008; Khose et al., 2021; Shekhar et al., 2022, Khose et al., 2022). It is described as the ability of a plant to absorb concentrations of carbon and prevent excessive water loss by controlling stomatal closure. WUE holds significance as it measures how efficiently a plant uses water to produce biomass or grain.

Water use efficiency is an important concept in wheat which is one of the most widely cultivated cereals in the world covering about 224.49 mha with an estimated yield of 792.40 million tonnes production. Wheat is India's second most important crop after rice and has been playing an important role in the country's food and nutritional security (Khose et al., 2022; Pohshna and Mailapalli, 2023). The wheat crop consumes 2-3 times less water compared to the rice crop but WUE and nitrogen use efficiency is very poor (Verma et al., 2023a; Verma et al., 2023b; Verma et al., 2023c). Therefore, an optimum water and nutrient application plays a very crucial role in increasing the WUE, nitrogen use efficiency (NUE), and plant growth and yield. It has been reported that in India about 30% of wheat production is due to lack of irrigation water and 40% due to lack of nutrient supply and environmental factors (Uddin et al., 2016; Islam et al., 2016).WUE and NUE are important indicators for measuring the efficiency of irrigation systems. Therefore, optimum irrigation water and nutrient supply can increase yield by up to 70% (Ahmed, 2006, Uddin et al., 2016). Hence studies on WUE and transpiration efficiency (TE) are necessary to maintain future food security and mitigate the climate change impacts on crop production.

A number of factors can affect WUE in wheat, including climate, soil, and crop management practices. For example, high temperatures and low rainfall can increase ET and reduce WUE. Sandy soils have lower water holding capacity than clay soils, which can also lead to lower WUE. Deficit irrigation, mulching, and nitrogen fertilization with limited irrigation are some of the practices that can be used to improve WUE in wheat (Zhao and Gao et al., 2020). Research on WUE in wheat has identified a number of pathways for maximizing food grain production and water productivity. For example, adjusting the crop water use (CWU) and adopting deficit irrigation in extensively irrigated areas can increase yield.

Overall, WUE is a critical concept in wheat production, and there are a number of practices that can be used to improve WUE. Various studies conducted on the importance of separating non-beneficial losses from beneficial losses in irrigation water application. They suggested that evaporation can be reduced and transpiration can be increased by changing irrigation frequency, method of irrigation, shading, mulching, and other practices (Burt et al., 1997). The experiments with 11 different genotypes of wheat to determineTE for the shoot and the entire plantwere conducted. They found that TE did not permit confident genotype differentiation due to poor estimates but showed differences at the harvesting and flag-leaf stage (Fletcher et al., 2018).

Water Use Efficiency from both engineering and agronomical perspectives suggested that WUE can be enhanced in four ways: increasing output per unit of evapotranspiration (ET), decreasing productive water losses to sinks, reducing water pollution by agrochemicals, salinity, nutrients, and sediments, and reallocating water for higher valued uses (Howell et al., 2001). Soil moisture plays a major role in the estimation of the soil water stress factor, ET, and thereby irrigation requirement (Khose and Mailapalli, 2023). Kang et al., (2002) measured parameters like soil water content, dry mass accumulation, photosynthesis rate, grain yield, and total water consumption to calculate wateruse efficiency and harvest index. They found a linear relationship between WUE and harvestindex and suggested that mild soil moisture depletion during the early vegetative growth period and severe soil moisture depletion during the maturity stage of wheat was the optimal condition for a limited irrigation regime.

The key to mitigating water shortage in an area is to increase WUE through biological and engineering measures like drip/sprinkler irrigation systems, furrow irrigation, mulching, terracing, and rainwater harvesting. Nitrogen fertilization with limited irrigation can also improve water productivity (Deng et al., 2006). Huang et al. (2005) conducted an experiment at the Dingxi Soil and Water Conservation Institute of the Loess Plateau to study the effects of rainfall on yield and the effect of irrigation and straw mulching. They found that rainfall was the primary factor limiting crop yields in rain-fed agriculture, with biomass and grain yield being extremely low and fluctuating greatly under rain-fed wheat. Zwart and Bastiaanssen (2004) reported that the average CWP of wheat, rice, cotton, and maize was higher than the reported by the FAO. Li et al., (2004) revealed that different irrigation regimes significantly affected plant transpiration, soil evaporation, and ET with a negative correlation between WUE and ET.

Thus, through proper planning and management of waterresources, water productivity can be increased by increasing efficiency and efficientirrigation (Ragab et al., 2008). The WUE with respect to photosynthesis, biomass, and grainyield basis under different irrigation regimes, finding a positive correlation between WUE and photosynthesis and grain yield (Qiu et al., 2008).

3. Impact of Different Water Application Levels on Wheat Crop

Water stress is a major constraint on crop production worldwide, and its effects are becoming increasingly severe due to climate change. Understanding the timing and duration of water stress periods, as well as their impact on different growth phases, is essential for developing effective water management strategies. Early research on water stress in corn revealed that it can cause substantial yield reductions, particularly during vegetative growth. Subsequent studies have investigated the relationship between water application levels and crop production, demonstrating the potential for enhancing yields and water use efficiency through optimized water management practices(Moteva and Kostadinov, 2019; Yang et al., 2022; Zeynoddin et al., 2023).

Expanding the discourse on water stress effects, recent studies have examined its impact on winter wheat. Findings suggest that moderate and severe stress conditions can significantly reduce photosynthetic parameters, leading to decreased height, biomass, and grain size. Notably, mild stress conditions may be considered optimal for winter wheat growth, supporting sustained production and efficient use of natural water resources. Overall, the research on water stress effects on crop growth and yield highlights the critical importance of water availability during all growth stages. Additionally, this research offers valuable insights for optimizing water management practices to achieve improved agricultural outcomes.

A comprehensive four-year investigation**(**Eck, 1986; Eck, 1988**)** conducted a study on the impact of water deficiency periods on corn growth and yield components in southern hill plains. They found that 2- and 4-week moisture stress periods during vegetative growth reduced corn production by 23 and 46%, respectively. Deficit periods during grain filling decreased by 17 and 33%. Decreases in leaf and stalk weights and kernel counts also decreased yield potential. Further studies found thatthe yield and water use efficiency of potatoes can be increased by applying water equivalent to 70-85% of ETc (Gebremariam et al., 2018). The evapotranspiration between the two planting patterns under the same deficit irrigation regime did not differ significantly, and WUE and grain yield were significantly higher in wide precision planting patterns than in the conventional cultivation planting pattern, irrespective of the irrigation regime (Li Quangi et al., 2010). This research contributed valuable insights into optimizing water management practices to achieve improved agricultural outcomes, emphasizing the practical implications for crop production. Zhao et al., (2020) found that seasonal variations in photosynthetic parameters decreased significantly under moderate and severe stress, leading to low WUE and IWP.

After a thorough review of studies,it was concluded that mild stress is the optimal environment for winter wheat growth to sustain production and efficiently use natural water. These studies provide valuable insights into the complex interplay between water availability, crop growth stages, and yield outcomes, emphasizing the need for tailored water management strategies to optimize agricultural productivity.

4. Impact of Nitrogen Application Levels on Wheat Crop

Nitrogen (N) is an essential macronutrient for winter wheat growth and development. Nfertilization is essential for achieving high yields, but it is important to optimize N rates andapplication timing to maximize crop yield and WUE while minimizing environmental impacts.The optimal N rate for winter wheat depends on a number of factors, including cultivar, soiltype, climate, and irrigation practices.

Research has shown that N application can increase leafarea, photosynthesis rates, chlorophyll content, and assimilation rates in winter wheat. However,N application rates above the optimal level can have a negative impact on yield and WUE. FoliarN fertilization can be an effective way to improve N uptake and utilization by winter wheat.Studies have shown that foliar N fertilization can increase leaf area, photosynthesis rates, andgrain yield compared to root-applied N fertilization. N fertilization is especially important forwinter wheat production in water-limited conditions.

Studies have shown that N fertilization canimprove WUE in winter wheat by increasing root growth and reducing water losses throughtranspiration. The optimal N rate for winter wheat depends on a number of factors, including cultivar, soiltype, climate, and irrigation practices.

Bar-Tal et al., (2001) found that the optimal N rate for drymatter production in winter wheat was 8.0–9.4 mmol·L^{-1}, while the maximum yield wasachieved at 8.2 mmol·L^{-1}. Above 10 mmol·L^{-1}, N concentration had a negative effect on yield. However, it is important to optimize N rates and application timing to maximize crop yield and WUE while minimizing environmental impacts.

Overall, the research on the impact of N fertilization on winter wheat growth and yield highlights the importance of N for all aspects of plant metabolism. Foliar N fertilization can be an effective way to improve N uptake and utilization by winterwheat. (Bar-Tal et al., 2001)found that plants supplied with foliar N had significantly higher leaf areas andphotosynthesis rates than plants supplied with N to the roots only**.** The Nfertilization increased chlorophyll content in the leaves and stems of winter wheat, and thatchlorophyll content was highest during anthesis.In comparison to the control treatment, N application increased the assimilation rate, WUE, andstomatal conductance of water vapor by an average of 51%, 60%, and 27%, respectively,according to a study on the effects of N fertilization on yield, WUE, chlorophyll content, and,photosynthetic characteristics of safflower grown under rainfed conditions (Dordas et al., 2008).The N availability is a rate-limiting factor for starch and sucrose synthesis and foliage growth atlow temperatures in white clover. The carbohydrate contents andphotosynthetic pigments are suitable indicators of the photosynthetic activity of winter wheat.

The insufficient N supply generally results in decreased root growth, reduction in photosynthesis,and early leaf senescence (Vagusevičienė et al., 2012). Irmak et al. (2012) conducted a study onmaize at different N fertilizer rates and irrigation levels. They found that full irrigation (FIT)with N fertilizer rates not exceeding 196 kg ha^{-1} could be recommended under non-water-limiting conditions, while limited irrigation (75% FIT) strategies with N fertilizer rates notexceeding 140 kg ha^{-1} could be recommended under water-limiting conditions to achieve a higheconomic return. The N application rates above N180 in wheat did not result in a significantincrease in grain yield (Litke et al., 2018). Overall, the research on the impact of N fertilization on winter wheat growth and yield highlightsthe importance of N for all aspects of plant metabolism. However, it is important to optimize Nrates and application timing to maximize crop yield and WUE while minimizing environmentalimpacts.

5. Integrated Impact of Water and Nitrogen Management on Wheat Crop Performance

Water and nitrogen (N) are essential resources for crop production, and their availability andmanagement can significantly impact yield and WUE. Optimizing water and N management iscritical for sustainable agriculture, especially in the face of climate change and increasing waterscarcity. Research on the interactions between water and N in crop production has shown that Nfertilization can increase WUE, while water availability can affect N uptake and utilizationefficiency. The optimal combination of water and N inputs depends on a number of factors,including crop species, cultivar, soil type, climate, and management practices. Recent researchhas focused on developing strategies for optimizing water and N management to improve cropyield and WUE. Some promising strategies include precision irrigation, drought-tolerant cropvarieties, and integrated nutrient management (INM). Overall, the research on the interactionsbetween water and N in crop production highlights the importance of optimizing water and Nmanagement to improve crop yield and WUE.

Zhang et al., (1998) studiedthe impact of nitrogen and irrigation on water usage, WUE, and transpiration efficiency (TE).They found that rain-fed conditions led to a decrease in water usage, while transpirationefficiency increased. Additionally, 35% of evapotranspiration for fertilized crops and 44% forunfertilized crops may be lost from the soil surface (Viets et al., 1962). Fertilized crops had a higher transpirationefficiency (TE) for dry matter and grain yield. In potato crops in northeast Portugal, irrigationclearly affected total tuber weight (t/ha), with the responsiveness of potatoes to irrigation beingmainly due to the longer growing season resulting from early sowing and a more incredibleoverall amount of water applied (Ferreira et al., 2007).The excessive use of water and nitrogen supply increased dry matter accumulation and had nosignificant effect on the yield as it increased the growth period but delayed the maturity, leadingto wastage of water and fertilizer loss (Wang et al., 2012).

Kiani et al., (2016) determined thecoupling effects of nitrogen and water under arid conditions for sunflower crops. They conducteda 2-year experiment using two sunflower hybrids under four different irrigation regimes rangingfrom over-irrigation to severe deficit irrigation and three nitrogen levels ranging fromunfertilized, 43, and 90 kg N /ha. They found that delayed sowing with reduced nitrogenfertilizer rates enhanced NUE though the grain yield remainedunchanged. The increasing nitrogen fertilization was beneficial, but excessive nitrogenapplication had no significant effect on LAI and yield (Li et al., 2021). The decreasing irrigationfrom 240 to 192 mm and reducing nitrogen fertilizer from 225 to 180 kg N ha^{-1} gave the samegrain yield due to enhanced water uptake efficiency and water use efficiency and promoted NUE(Tan et al., 2021). Wang s (2021) observed that different couplings of water and fertilizerapplication would affect photosynthesis and nitrogen accumulation in the soil, affecting thegrowth and yield of sunflowers.Overall, the research on the interactions between water and N in crop production highlights theimportance of optimizing water and N management to improve crop yield and WUE. Precisionirrigation, drought-tolerant crop varieties, and integrated nutrient management are somepromising strategies for achieving this goal.

6. Conclusion

The study found that understanding the timing and duration of water stress periods is essential for developing effective water management strategies. Moderate and severe stress conditions can significantly reduce photosynthetic parameters, leading to decreased height, biomass, and grain size. Mild stress conditions may be considered optimal for winter wheat growth, supporting sustained production and efficient use of natural water resources. A linear relationship between WUE and harvest index in wheat, suggests that mild soil moisture depletion during the early vegetative growth period and severe soil moisture depletion during the maturity stage is optimal for limited irrigation regimes.

Nitrogen fertilization with limited irrigation can improve water productivity, but application rates above the optimal level can negatively impact yield and WUE. Foliar nitrogen fertilization can be an effective way to improve N uptake and utilization by winter wheat, increasing leaf area, photosynthesis rates, and grain yield compared to root-applied N fertilization. Full irrigation (FIT) with N fertilizer rates not exceeding 196 kg ha−1 could be recommended under non-water-limiting conditions, while limited irrigation (75% FIT) strategies with N fertilizer rates not exceeding 140 kg ha−1 can be recommended under water-limiting conditions to achieve a high economic return.

The research highlights the critical importance of water availability during all growth stages and offers valuable insights for optimizing water management practices to achieve improved agricultural outcomes. It also emphasizes the need for tailored water management strategies to optimize agricultural productivity. Timely and accurate information about water and nutrient status is crucial for fertilizer application and irrigation scheduling, and increasing production with less water.

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