Postprint: Mechanisms and Technologies for Efficient Multi-Source Water Utilization in Low-Plain Farmlands of the Bohai Rim

Authors: Zhang Xiying, Liu Xiaojing, Chen Suying, Sun Hongyong, Shao Liwei, Niú Jūnfǎng

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Abstract

Severe freshwater scarcity is a critical limiting factor affecting the sustainable development of grain production in the Bohai Rim low plain region. This paper addresses the low water use efficiency and substantial improvement potential in grain production in this area, while considering the relatively abundant shallow brackish water resources and precipitation. Based on experimental research results from the Nanpi Eco-Agricultural Experimental Station of the Chinese Academy of Sciences over the past three years, it reviews research progress in tapping the potential of brackish water utilization and improving rainwater and irrigation water use efficiency. For the winter wheat-summer maize double-cropping system, research results show significant differences in yield and water use efficiency (WUE) among varieties, with differences between the highest and lowest varieties reaching approximately 20%; selecting water-saving and high-yield varieties can significantly improve yield and WUE. For winter wheat, irrigating critical water at the jointing stage not only promotes aboveground biomass accumulation but also significantly promotes underground root growth, enabling winter wheat to fully utilize soil water storage and achieve stable and efficient production under limited irrigation. For summer maize, reduced-row uniform sowing (narrowing row spacing while increasing plant spacing) can increase the soil volume space occupied by the root system per plant during the seedling stage, enhance the availability of water and nutrients to the crop, improve seedling establishment rate and radiation interception during the seedling stage, and increase yield by approximately 10% compared to conventional planting. Winter wheat irrigated with shallow brackish water (salinity $\leq 4\ \mathrm{g \cdot L^{-1}}$) at the jointing stage achieves the same yield as freshwater irrigation. The substitution of freshwater with shallow brackish water irrigation, combined with soil organic matter enhancement techniques and summer precipitation leaching of salts, can achieve annual soil salt balance under brackish water irrigation.

Through the implementation of these measures, the complementary and efficient utilization of multiple water sources can be achieved—using brackish water to supplement freshwater and freshwater to regulate salinity—thereby conserving deep freshwater resources without affecting crop yield and promoting the sustainable development of regional irrigated agriculture.

Full Text

Preamble

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Efficient Utilization of Various Water Sources in Farmlands in the Low Plain Nearby Bohai Sea*

ZHANG Xiying, LIU Xiaojing, CHEN Suying, SUN Hongyong, SHAO Liwei, NIU Junfang
(Key Laboratory of Agricultural Water Resources, Chinese Academy of Sciences / Hebei Laboratory of Water-saving Agriculture / Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050022, China)

Abstract

Severe freshwater scarcity represents a critical constraint on sustainable grain production in the low plain region surrounding the Bohai Sea. This paper addresses the dual challenges of low water use efficiency and substantial improvement potential in regional grain production, while leveraging the relatively abundant shallow brackish water and precipitation resources. Based on three years of experimental research conducted at the Nanpi Eco-Agricultural Experimental Station of the Chinese Academy of Sciences, we review recent advances in tapping the potential of saline water utilization and improving the efficiency of rainwater and irrigation water use. For the winter wheat-summer maize double-cropping system, results demonstrate significant cultivar differences in both yield and water use efficiency (WUE), with differences between the highest- and lowest-performing cultivars reaching approximately 20%. Selecting water-saving, high-yield cultivars can substantially enhance both yield and WUE. For winter wheat, a single irrigation at the jointing stage promotes both aboveground biomass accumulation and root growth, enabling efficient utilization of soil-stored water and achieving stable, high-efficiency production under limited irrigation. For summer maize, reducing row spacing while increasing plant spacing—termed "narrow-row uniform planting" —enhances the soil volume accessible to individual seedlings, improves water and nutrient availability, increases seedling establishment rates, and boosts radiation interception during the seedling stage, resulting in approximately 10% higher yields compared with conventional planting. Using shallow brackish water with salinity not exceeding

4 g $\cdot$ L^{-1} as a substitute for freshwater irrigation at the jointing stage of winter wheat produces yields equivalent to freshwater irrigation. When combined with soil organic matter enhancement techniques and summer rainfall leaching, this approach achieves annual soil salt balance under brackish water irrigation. Implementation of these measures enables "supplementing freshwater with brackish water, regulating salt with freshwater, and achieving efficient multi-source water complementarity," conserving deep freshwater resources without compromising crop yields and promoting sustainable development of irrigated agriculture in the region.

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The water crisis represents one of humanity' s most severe challenges. Currently, 70% of global water resources are allocated to agricultural production, yet future industrial development and urbanization will progressively reduce water availability for agriculture while population growth demands increased food production. Resolving the conflict between water scarcity and food production has become a worldwide priority. The low plain surrounding the Bohai Sea constitutes a vital agricultural production region in China, playing a crucial role in national food security. However, this area ranks among China' s most water-scarce regions, with per capita and per-unit cultivated land water availability of only 190 m^3 $\cdot$ person^{-1} and 1,650 m^3 $\cdot$ hm^{-2}—merely 1/12 and 1/16 of the national average, respectively. Grain production has long relied on extracting deep groundwater, causing continuous water table decline and creating the world' s largest groundwater funnel with associated environmental problems. Paradoxically, the region exhibits low water use efficiency in grain production with substantial improvement potential, while possessing renewable shallow brackish water resources currently utilized at less than 40% and relatively abundant annual precipitation of 450-600 mm. Therefore, addressing extreme freshwater scarcity, low water use efficiency, and underutilized brackish water and precipitation resources, this research focuses on tapping brackish water potential, improving groundwater and rainwater use efficiency, and achieving multi-source water complementarity to support grain production increases without increasing regional agricultural freshwater consumption, thereby providing water resource security for the "Bohai Granary" initiative. This paper synthesizes recent research findings from the Nanpi Eco-Agricultural Experimental Station (hereinafter "Nanpi Station") to inform regional multi-source water utilization technology development and application.

1. Improving Farmland Water Use Efficiency

"Producing more grain with every drop of water" represents a global scientific consensus for addressing water scarcity through enhanced agricultural water use efficiency. As crop water consumption occurs primarily in the field, agronomic water-saving measures to improve natural precipitation and irrigation water use efficiency constitute a critical dimension of farmland water conservation. Research indicates that current global average water productivity for the three major crops—rice, wheat, and maize—stands at 1.09 $\mathrm{kg \cdot m^{-3}}$, 1.09 $\mathrm{kg \cdot m^{-3}}$, and 1.80 $\mathrm{kg \cdot m^{-3}}$, respectively, while optimized levels can reach 1.60 $\mathrm{kg \cdot m^{-3}}$, 1.70 $\mathrm{kg \cdot m^{-3}}$, and 2.70 $\mathrm{kg \cdot m^{-3}}$, revealing tremendous improvement potential and underscoring the importance of developing highly water-efficient agriculture.

According to 2011 Hebei Provincial statistics, average winter wheat and maize yields in the Hebei low plain currently reach 5,569.5 $\mathrm{kg \cdot hm^{-2}}$ and 6,468 $\mathrm{kg \cdot hm^{-2}}$, respectively. Based on irrigation quotas, growing season precipitation, and differential soil water utilization capacities, average seasonal water consumption amounts to 420 mm for winter wheat and 380 mm for summer maize, yielding current water use efficiencies of 1.33 $\mathrm{kg \cdot m^{-3}}$ and 1.70 $\mathrm{kg \cdot m^{-3}}$. Maintaining current water consumption while improving WUE to the high-yield level of the piedmont plain (1.50 $\mathrm{kg \cdot m^{-3}}$ and 2.00 $\mathrm{kg \cdot m^{-3}}$) would increase winter wheat and summer maize yields by 730.5 $\mathrm{kg \cdot hm^{-2}}$ and 1,132.5 $\mathrm{kg \cdot hm^{-2}}$, respectively, achieving an annual yield increase of 1,863 $\mathrm{kg \cdot hm^{-2}}$. With current irrigated areas of 970,400 $\mathrm{hm^2}$ for winter wheat and 869,900 $\mathrm{hm^2}$ for summer maize in the low plain, this translates to an annual production increase of 1.69 billion kg without additional water consumption, equivalent to conserving 1.11 billion $\mathrm{m^3}$ of water resources. Further improvements in irrigation infrastructure and high-yield cultivation techniques to achieve higher WUE levels (1.70 $\mathrm{kg \cdot m^{-3}}$ for wheat and 2.20 $\mathrm{kg \cdot m^{-3}}$ for maize) could reduce field water consumption by 40 $\mathrm{mm \cdot a^{-1}}$ while increasing yields by 1,231.5 $\mathrm{kg \cdot hm^{-2}}$ and 1,452 $\mathrm{kg \cdot hm^{-2}}$, respectively, achieving an annual yield increase of 2,683.5 $\mathrm{kg \cdot hm^{-2}}$ and total production gains of 1.69 billion kg, reducing agricultural irrigation water use by 368 million $\mathrm{m^3}$—equivalent to conserving 1.64 billion $\mathrm{m^3}$ of freshwater resources. These results demonstrate the critical importance of improving farmland water use efficiency for regional water-saving agriculture.

1.1. Selecting Water-Saving High-Yield Cultivars to Improve Yield and Water Use Efficiency (WUE)

Biological water conservation harnesses the physiological and genetic potential of crops to achieve greater agricultural output under identical water conditions. Numerous studies demonstrate that different crops produce varying amounts of dry matter per unit of water consumed (water use efficiency), and significant differences exist among cultivars of the same crop. Farmland water use efficiency (WUE) is defined as WUE = (biomass × harvest index) / farmland water consumption, which can be enhanced through three pathways: increasing biomass, raising harvest index, and reducing water consumption. Both harvest index and biomass accumulation are closely related to genetic improvement and enhanced crop growth conditions.

Zhang et al. investigated winter wheat cultivars widely promoted across different eras in the Hebei Plain when grown under modern conditions, finding that current cultivars showed significant yield increases and improved WUE while maintaining stable water consumption. Cultivar improvement contributed to an average annual yield increase of 1% and WUE enhancement of 0.5%, with improved WUE closely associated with accelerated phenological development and higher harvest indices. Modern cultivars also exhibit significant variation in yield and WUE, and the process of screening high-yielding varieties simultaneously improves farmland water use efficiency. As shown in [Figure 1: see original paper], cultivar comparison trials at Nanpi Station (2014–2015) revealed yield differences of up to 28% between the highest- and lowest-performing varieties, underscoring the importance of cultivar selection for improving yield and WUE. However, cultivar performance varies across years due to interannual weather fluctuations. Zhang et al. demonstrated that under climate change, weather-driven yield potential in the 21st century is approximately 10% lower than in the 1980s, indicating increasingly unfavorable conditions for major crops in Hebei that prevent full expression of yield and WUE potential. These adverse conditions manifest as greater increases in minimum than maximum daily temperatures (reducing diurnal temperature range), declining wind speeds and sunshine hours, increased average temperatures during both crop growing seasons, and higher probabilities of extreme temperature events—particularly abrupt cooling during late maize grain filling and large spring temperature fluctuations, rapid warming, and dry-hot wind events during late winter wheat grain filling. Consequently, new cultivars adapted to these changing climate conditions are needed to fully realize crop biological water-saving and yield-enhancement potential.

1.2. Optimizing Winter Wheat Irrigation Scheduling

As water scarcity intensifies, irrigation strategies have shifted from full irrigation to water-saving approaches such as limited irrigation, deficit irrigation, and regulated deficit irrigation, facilitating the transition from high-water-input/high-yield systems to water-saving/optimal-yield systems that improve WUE. Research demonstrates that crop physiological and ecological indicators exhibit threshold responses to soil moisture, with reductions in soil water content above certain levels having no impact on these indicators. For winter wheat in the Bohai Rim region, the short grain-filling period and susceptibility to dry-hot winds often prevent full yield potential expression. Under moderate water deficit, winter wheat development accelerates, the grain-filling period extends moderately, and post-anthesis dry matter accumulation and translocation to grain improve, ultimately increasing harvest index.

presents three growing seasons (2012–2015) of irrigation experiments at Nanpi Station with normal precipitation levels. Two irrigations produced maximum yield, with additional applications yielding no further increases or even causing reductions. WUE declined with increasing irrigation frequency. Across the three seasons, adding one irrigation at jointing stage to rain-fed conditions increased yield by 30.7%; adding a second irrigation to the jointing-stage treatment increased yield by only 5.7%, while a third irrigation caused a 2.5% yield reduction. WUE decreased by 2.2%, 3.5%, and 14.8% when moving from rain-fed to one irrigation, one to two irrigations, and two to three irrigations, respectively. These results indicate that one to two irrigations produce relatively high yields and WUE in most years. also reveals substantial interannual yield variation: despite similar precipitation between the 2013–2014 and 2014–2015 seasons, maximum yield in 2013–2014 exceeded that of 2014–2015 by 17%, demonstrating that weather conditions significantly influence winter wheat yield formation beyond irrigation effects.

Located in a monsoon climate zone, the Bohai Rim low plain receives concentrated summer rainfall, with winter wheat growing season precipitation (October–June) far below crop water requirements. Rational irrigation not only facilitates effective soil water utilization but also plays a crucial role in improving winter wheat WUE. Before regreening, winter wheat water uptake concentrates in the upper 80 cm soil layer; during jointing to flowering, rapid root growth increases water uptake from below 80 cm, and during grain filling, minimally irrigated wheat relies primarily on middle and deep soil water storage. Nanpi Station experiments across three seasons found that soil water depletion accounted for 52.3%, 43.4%, 30.4%, and 19.4% of seasonal evapotranspiration under zero to three irrigation treatments, respectively, highlighting the importance of soil water utilization for stable, efficient production under limited irrigation. Research indicates that root length densities below 0.8 $\mathrm{cm} \cdot \mathrm{cm}^{-3}$ become limiting factors for adequate soil water absorption, with insufficient deep roots restricting utilization of deep soil water storage. Zhang et al. demonstrated that under limited irrigation, winter wheat requires adequate water during vegetative growth to establish sufficient biomass and promote root system development, laying the foundation for full soil water utilization during grain filling. Evapotranspiration during this stage significantly affects final yield; poor water conditions restrict aboveground growth and subsequent root development, ultimately limiting yield under deficit irrigation. Therefore, efficient water use patterns for winter wheat should employ irrigation during vegetative growth to promote both aboveground and root development, enabling full utilization of soil water storage during reproductive growth. Accordingly, the optimal irrigation timing under limited water conditions is the jointing stage, as this promotes both shoot and root growth, creating conditions for later-season soil water utilization.

1.3. Supporting Cultivation Measures to Improve Maize Yield and WUE

Complementary cultivation measures constitute an important approach to enhancing crop water use efficiency. Different crops and cultivars exhibit physiological, ecological, and morphological differences in environmental requirements and adaptability; only when environmental conditions align with cultivar characteristics can genetic potential be fully expressed and resources rationally utilized. Numerous studies demonstrate significant positive correlations between sunlight during the summer maize growing season and grain yield. However, the Hebei low plain faces deteriorating light conditions, with total sunshine hours during the maize growing season decreasing by an average of 4.9 hours annually from the 1950s to present, declining from 1,000 hours to 700 hours ([Figure 2: see original paper]). Consequently, maximizing light energy utilization has become crucial for high yield and efficiency.

In the Bohai Rim low plain' s winter wheat-summer maize double-cropping system, the short maize growing season can be extended through delayed harvest and earlier planting, increasing intercepted radiation and ultimately improving yield. Nanpi Station research indicates that delaying maize harvest from September 22 to September 30 increases 100-grain weight by approximately 10%. Since water use efficiency during grain filling (2.5-4 $\mathrm{kg \cdot m^{-3}}$) far exceeds that of the entire growing season (2.0 $\mathrm{kg \cdot m^{-3}}$), delayed harvest not only increases yield but also improves seasonal WUE. However, under climate change, large temperature fluctuations in late September often cause cooling below the threshold required for grain filling, halting the process prematurely and preventing yield gains from delayed harvest alone, necessitating combination with earlier planting strategies.

Planting density and row spacing arrangement affect maize canopy structure and root spatial distribution, influencing light interception and water/nutrient availability, thereby impacting yield and WUE. Nanpi Station research examined four configurations at identical density (67,500 $\mathrm{plants \cdot hm^{-2}}$): 20 cm–100 cm and 40 cm–80 cm wide-narrow rows, 60 cm–60 cm equal rows, and 38 cm uniform spacing. Root sampling revealed competitive relationships between adjacent plants in wide-narrow row configurations, while reduced row spacing with increased plant spacing (enhanced spatial uniformity) increased individual plant soil volume access, improving water and nutrient availability and reducing interplant competition. Under drought-prone seedling conditions, uniformly spaced plants obtained significantly more soil water, increasing seedling establishment rates by 10%–15% ([Figure 3: see original paper]). Uniform planting also increased photosynthetically active radiation interception during the seedling stage, significantly improving both yield and WUE. These results demonstrate the importance of optimized cultivation management for realizing maize yield and efficiency potential.

2. Improving Rainwater Resource Utilization Efficiency

In freshwater-scarce regions, farmland tillage and mulching measures that maximize rainwater storage and reduce irrigation dependence represent crucial pathways for improving limited-irrigation crop yields. Rainwater harvesting techniques include deep tillage, subsoiling, harrowing, compaction, and conservation tillage. Conservation tillage replaces traditional intensive cultivation with reduced or no-till practices while using straw, stubble, or vegetation cover to reduce erosion and evaporation, minimize soil structural disruption, improve water retention, and significantly increase yields. Subsoiling breaks plow pans, deepens the loose soil layer, enhances rainwater storage capacity, and promotes deep root water uptake, reducing excessive dependence on surface soil moisture. Harrowing and compaction reduce surface macropores and evaporation through soil fragmentation, leveling, and surface compaction.

The winter wheat-summer maize rotation in the Bohai Rim low plain generates abundant crop straw, and returning straw to fields offers low-cost benefits for moisture conservation, temperature regulation, and soil fertility improvement while providing optimal straw utilization. Research shows that direct straw mulching after winter wheat harvest reduces summer maize season soil evaporation by 30-40 mm, with this conserved water stored for subsequent winter wheat use. Under limited irrigation, 40%-50% of winter wheat water consumption derives from soil water storage, making straw mulching crucial for reducing irrigation water consumption in the wheat-maize rotation. However, while maize straw mulching for winter wheat raises soil temperature in winter, it retards spring warming, delaying wheat phenology, causing delayed maturity, and potentially reducing grain weight and WUE.

Plastic film mulching interrupts soil-atmosphere water exchange, effectively suppressing surface evaporation, raising soil temperature, advancing crop maturity, and controlling weeds more effectively than straw mulching. Experiments during the 2013-2014 winter wheat season compared flat mulching with soil-covered film and ridge-furrow mulching, both of which reduced inter-plant evaporation while the ridge-furrow system collected light rainfall, reducing evaporation losses and increasing precipitation effectiveness. As shown in , both mulching methods increased winter wheat yield by 6%-10% and WUE by 10%-11%, with ridge-furrow mulching outperforming flat mulching by effectively collecting rainwater while the latter' s soil layer above the film may impede rainfall infiltration. However, plastic mulching may reduce soil fertility and cause pollution from uncollected waste film, necessitating use of new biodegradable environmentally friendly films.

Beyond efficient farmland rainwater utilization, the Bohai Rim low plain' s numerous ponds (formed from abandoned kilns, fishponds, and construction excavation) can store summer runoff and external water, increasing available irrigation sources. Regional pond storage capacity totals 800 million m^3, intercepting over 40% of precipitation-generated runoff during concentrated summer rainfall months. In Nanpi County, interconnected drainage ditches and ponds store both rainwater and diverted water, with some areas maintaining shallow groundwater levels. This stored water can irrigate winter wheat during dormancy and regreening stages or provide pre-planting irrigation to store water in soil, reducing groundwater extraction and surface evaporation losses.

3. Tapping the Potential of Shallow Brackish Water

The Bohai Rim region possesses substantial underground brackish water reserves totaling 250 billion m^3, with annual exploitable resources of $<5\ g \cdot L^{-1}$ micro-saline water accounting for half of the national total. In the Hebei low plain, micro-saline water resources ($<5\ g \cdot L^{-1}$) amount to 1.099 billion m^3, currently utilized at only 40% (), leaving 60% available for agricultural use and providing nearly 750 $m^3 \cdot hm^{-2}$ of additional irrigation water. Based on crop salt tolerance and water requirements, supplemental irrigation with brackish water during specific growth stages can substitute for freshwater or increase water supply to achieve yield gains. The region' s monsoon climate with concentrated summer precipitation enables salt leaching, maintaining soil salinity within safe ranges. Therefore, rational brackish water exploitation provides important water resource security for grain production increases in the Bohai Rim low plain.

3.1. Optimizing Brackish Water Irrigation Timing

Winter wheat and summer maize exhibit different salt sensitivities and seasonal precipitation patterns. Winter wheat demonstrates greater salt tolerance than summer maize, with soil saturated paste extract electrical conductivity thresholds for initial yield reduction of 4.0 $dS \cdot m^{-1}$ and 1.7 $dS \cdot m^{-1}$, respectively, and 50% yield reduction thresholds of 13.0 $dS \cdot m^{-1}$ and 5.9 $dS \cdot m^{-1}$. Winter wheat' s low-rainfall growing season requires irrigation for high, stable yields, and its salt tolerance enables brackish water substitution for freshwater or additional brackish water applications to achieve yield goals. Conversely, summer maize' s rainy growing season can be satisfied through rainwater collection and utilization in most years, creating favorable soil moisture conditions for subsequent winter wheat. However, due to differential salt sensitivities, brackish water irrigation effects on subsequent crops and long-term soil salt balance must be considered.

presents three-year brackish water irrigation experiments at Nanpi Station. Adding one irrigation to rain-fed conditions, whether with freshwater or $<5\ g \cdot L^{-1}$ brackish water, increased winter wheat yield by 20%-50%, with similar effects between brackish and freshwater. Substituting brackish water for freshwater irrigation did not significantly affect yield. The optimal timing for both additional and substitutive brackish water irrigation is around the jointing stage, confirming the broad applicability of brackish water irrigation for winter wheat. However, salt accumulated from winter wheat brackish water irrigation, particularly in the 0-20 cm root zone of summer maize seedlings, increases soil salinity by 10%-30% ([Figure 4: see original paper]), necessitating mitigation of salt effects on maize germination and early growth for successful double-cropping systems.

To ensure summer maize yield is not compromised by winter wheat brackish water irrigation, freshwater irrigation exceeding 70 mm at maize sowing is required to leach salts from the root zone below the maize salt tolerance threshold. Alternatively, localized irrigation can create a desalinized micro-environment for seed germination with reduced water volume, with subsequent monsoon rainfall achieving complete root zone desalinization and preventing salt accumulation. Localized irrigation techniques include micro-irrigation and furrow irrigation systems.

3.2. Enhancing Soil Buffering Capacity Through Straw Return to Support Long-Term Brackish Water Irrigation

While using \$ $5g \cdot L$^{-1}\$ brackish water to substitute for or supplement freshwater at the critical jointing stage of winter wheat demonstrates clear yield and water-saving benefits, alleviating freshwater shortages, concerns persist regarding long-term salt accumulation and potential yield reduction. Research indicates that irrigation with saline water exceeding certain thresholds can cause soil salt concentration, disrupt plant peroxide metabolism, reduce photosynthesis, and decrease yields. However, modern agricultural development, particularly mechanized full straw return in the Bohai Rim wheat–maize system, has substantially improved soil fertility and organic matter content, enhancing soil buffering capacity against harmful ions and reducing brackish water irrigation impacts over time.

In Nanpi County, topsoil organic matter increased from 8.9 $\mathrm{g \cdot kg^{-1}}$ in 1981 to 15.6 $\mathrm{g \cdot kg^{-1}}$ by 2015, driven by long-term straw return and increased fertilizer input. Elevated soil organic matter improves soil structure, mitigating the negative effects of brackish water irrigation on soil physicochemical properties. As shown in [Figure 5: see original paper], the proportion of water-stable aggregates increases linearly with soil organic matter content, playing a vital role in maintaining soil structure and enhancing salt leaching. Increased organic matter raises the salinity threshold for viable brackish water irrigation, supporting use of higher-salinity water. [Figure 6: see original paper] summarizes Nanpi County micro-saline water irrigation experiments since the 1980s, showing that as soil organic matter increased, the yield response to 4 $\mathrm{g \cdot L^{-1}}$ high-salinity water gradually matched that of 2 $\mathrm{g \cdot L^{-1}}$ low-salinity water, with equivalent yields achieved at 18 $\mathrm{g \cdot kg^{-1}}$ organic matter, demonstrating that long-term straw return significantly enhances soil buffering capacity.

Increased soil organic matter promotes beneficial microbial communities, improves plant $\mathrm{K^+/Na^+}$ ratios, enhances osmotic adjustment substance absorption, accelerates nutrient cycling, and boosts antioxidant enzyme synthesis, raising crop salt tolerance thresholds. [Figure 7: see original paper] shows that applying decomposed organic manure significantly reduces $\mathrm{Na^+/K^+}$ ratios in winter wheat flag leaves, which is crucial for maintaining yields under higher-salinity irrigation. However, some manure types may exacerbate salt effects due to varying salt contents; for example, pig manure contains 1.2% total salt compared with 0.4% in decomposed straw. Ahmed et al. demonstrated that poultry manure application reduced yields under high-salinity irrigation (2 $\mathrm{dS \cdot m^{-1}}$), while straw-derived organic matter increased yields across all irrigation treatments. Therefore, long-term straw return represents a more meaningful approach for enhancing soil buffering capacity under brackish water irrigation.

To meet water resource demands for grain production increases in the Bohai Rim' s medium-low yield areas while alleviating freshwater shortages, safe and efficient brackish water utilization is essential—both through "source development" to increase water supply and "consumption reduction" through improved WUE. Recent Nanpi Station research demonstrates that integrated measures including water-saving cultivar selection, narrow-row uniform maize planting, and deficit irrigation for winter wheat can improve water productivity from current levels of 1.5 $\text{kg} \cdot \text{m}^{-3}$ (wheat) and 1.8 $\text{kg} \cdot \text{m}^{-3}$ (maize) to higher levels of 1.8 $\text{kg} \cdot \text{m}^{-3}$ and 2.4 $\text{kg} \cdot \text{m}^{-3}$, respectively, achieving water-saving potential of 2.0–2.4 billion m^3 under current production conditions. Concurrently, long-term straw return continuously increases soil organic matter, reducing adverse effects of brackish water substitution and creating conditions for safe long-term use, providing nearly 750 $\text{m}^3 \cdot \text{hm}^{-2}$ of irrigation water for local farmland.

Based on these findings, grain production in the Bohai Rim involves multiple water sources including groundwater (brackish and fresh

Note: Figure translations are in progress. See original paper for figures.

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