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Integrated Irrigation and Disease Management Strategies for Sustainable Wheat Production and Improved Plant Health and Grain Yield

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ABSTRACT

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Wheat production was expected to provide reliable grain quality and farmer income while using less water and facing climatic variability, soil degradation, disease development, and rising energy costs. This literature-based paper critically synthesized verified research on irrigation, plant disease management, irrigation-disease interactions, sustainability, digital agriculture, and the Pakistan/developing-economy context. It considered irrigation and plant health as related management areas rather than completely separate input decisions. The available evidence did not identify a universal irrigation technology or deficit percentage. Instead, it supported a context-specific approach that considered stored soil water and rainfall, protected important growth stages, managed canopy humidity and nitrogen, used resistant cultivars and clean seed, and applied surveillance, forecasting, and fungicides when justified. Global and China-focused studies reported that moderate deficit or optimized water-saving irrigation could improve water productivity, whereas severe water deficit commonly reduced yield. Jointing/stem elongation was repeatedly identified as an important stage for avoiding water stress, while anthesis and early grain filling were also important when water availability and disease risk required attention. Disease-management evidence emphasized genetic resistance, sanitation, crop rotation, scouting, and forecasting before chemical control. Fusarium head blight required particular attention to weather conditions around anthesis, residue inoculum, cultivar resistance, fungicide timing, and deoxynivalenol risk. Irrigation increased yield without increasing disease in some environments, although dense nitrogen-rich canopies, overhead wetting, and saturated soils could favor foliar diseases and waterlogging. Digital tools were considered decision-support infrastructure that linked observations, analysis, and management actions. Wheat-specific evidence was relatively stronger for soil-moisture scheduling and weather-based stripe-rust forecasting, whereas many claims involving artificial intelligence, UAVs, and variable-rate irrigation remained predictive or transferable rather than directly supported by causal field evidence. Evidence from Pakistan indicated dependence on groundwater, salinity and waterlogging problems, uneven disease surveillance, and barriers to technology adoption. Differences among official statistics also indicated the need for careful reconciliation rather than simple averaging. The paper proposed an integrated framework involving diagnosis, planning, stage-aware irrigation, plant-health protection, evaluation, and seasonal feedback. It also identified the need for multi-location and multi-season studies that evaluated water use, disease, grain quality, energy use, greenhouse-gas emissions, profitability, and equity together.

Introduction

Wheat (*Triticum aestivum* L.) is a central food, feed, and income crop whose productivity depends on the interaction of water supply, soil condition, nitrogen nutrition, cultivar genetics, weather, disease pressure, and farm management. Irrigation is often discussed as a yield-increasing input, while disease management is discussed as a crop-protection activity. That separation is analytically convenient but agronomically incomplete. Water determines tiller survival, leaf area, spike fertility, grain filling, nutrient uptake, and the duration of green tissue. The same water and nitrogen decisions also shape canopy density, leaf-wetness duration, air movement, and the microclimate experienced by rusts, *Septoria tritici* blotch, powdery mildew, and *Fusarium* head blight (FHB). Consequently, an irrigation practice can protect a crop from drought while increasing humidity risk, or can save water while increasing stress-related yield and quality loss.

The challenge is not simply to maximize yield per hectare. Sustainable wheat management must consider yield stability, water productivity, irrigation withdrawal, groundwater depletion, soil salinity, waterlogging, pumping energy, nitrogen-use efficiency, greenhouse-gas (GHG) emissions, grain protein, test weight, gluten and baking traits, mycotoxin risk, profitability, and equitable access. A high water-productivity ratio can be achieved by cutting water so severely that yield, income, or food supply declines. Conversely, high yield under excessive irrigation may conceal poor water productivity, leaching, energy use, root-zone saturation, or downstream effects. The distinction between crop water productivity (yield divided by evapotranspiration or specified crop water use), irrigation water-use efficiency (yield divided by irrigation applied), and a modeled benchmark is therefore essential (Yu et al., 2020; Zwart et al., 2010).

Evidence increasingly favors stage-aware and threshold-aware management. Meta-analytic results report that deficit irrigation can increase wheat water-use efficiency while reducing average yield, whereas optimized water-saving irrigation can reduce applied water without a significant overall yield penalty in a different evidence base (Ma et al., 2025; Yu et al., 2020). Jointing or stem elongation is commonly identified as a high-value stage for avoiding severe water stress, with anthesis and early grain filling important in many high-yield or disease-risk contexts (Si et al., 2023). Yet no universal fraction of full irrigation applies across soils, climates, cultivars, rainfall regimes, rooting depths, and technologies.

Disease management has a similarly conditional evidence base. Genetic resistance is the most sustainable first line against rusts, FHB, *Septoria*, powdery mildew, and seed-borne disease, but resistance can be incomplete, race-specific, or eroded by pathogen evolution (Figueroa et al., 2018; Rehman et al., 2024). Clean or certified seed, residue and rotation management, scouting, weather information, forecasting, and targeted registered fungicides form a hierarchy. Fungicides are neither a substitute for resistance nor a guarantee of grain safety: symptom suppression does not necessarily remove deoxynivalenol (DON), and late treatment cannot reverse toxin already accumulated (Alisaac & Mahlein, 2023; Wegulo et al., 2013).

Research problem

The research problem is a fragmented evidence and management system. Irrigation studies often report yield or water productivity without disease severity, leaf wetness, DON, soil salinity, energy, or profitability. Disease studies often discuss moisture and canopy conditions without measuring root-zone water balance, irrigation withdrawal, drainage, or water-use efficiency. Digital agriculture studies may report model accuracy without showing that a forecast changed an irrigation or fungicide decision and improved farm outcomes. Pakistan evidence further reveals a gap between broad water and disease concerns and integrated causal evidence under farmer conditions.

This fragmentation produces three practical risks. First, a water-saving recommendation can be adopted without understanding yield, grain-quality, disease, or groundwater consequences. Second, a disease-control recommendation can be applied through excessive irrigation or nitrogen that creates a dense, humid canopy. Third, a technology may be promoted because it is accurate or efficient in a single site, even though calibration, maintenance, finance, connectivity, service markets, and equity determine whether it works in practice.

Research gap

The most defensible gap is the absence of a verified Pakistan-relevant, multi-location, multi-season causal evaluation of an integrated package linking irrigation scheduling and method, drainage and salinity, cultivar and integrated pest management (IPM), nitrogen, grain quality, disease and toxin outcomes, resource footprints, profitability, and adoption. The supplied evidence does not justify claiming that one device, irrigation method, deficit percentage, or AI model is the missing solution. Rather, promising components exist separately, but external validity and causal integration are weak.

A second gap concerns measurement. Studies use different definitions of deficit irrigation and different water-productivity denominators. Many trials measure final yield but not the pathway through soil moisture, canopy humidity, infection timing, nutrient movement, energy, or grain quality. A third gap is implementation: farmers may lack affordable equipment, credit,

repair services, reliable electricity, extension, certified seed, or timely disease advisories. The literature therefore requires synthesis that distinguishes measured effects, modeled results, observational associations, recommendations, and conceptual proposals.

Scope and evidence discipline

This is a literature-based academic paper, not a new empirical field study. It uses only verified research notes and source details supplied in the project directory. Numerical values are retained with their original study context and are not pooled anew. References include peer-reviewed studies, meta-analyses, official statistics, international-agency reports, and extension or operational guidance where those source types are appropriate. Internal note labels are not used as citations. The paper uses APA 7 author-date citations and labels modeled, observational, advisory, and conceptual claims.

Integrated irrigation + disease management loop for sustainable wheat

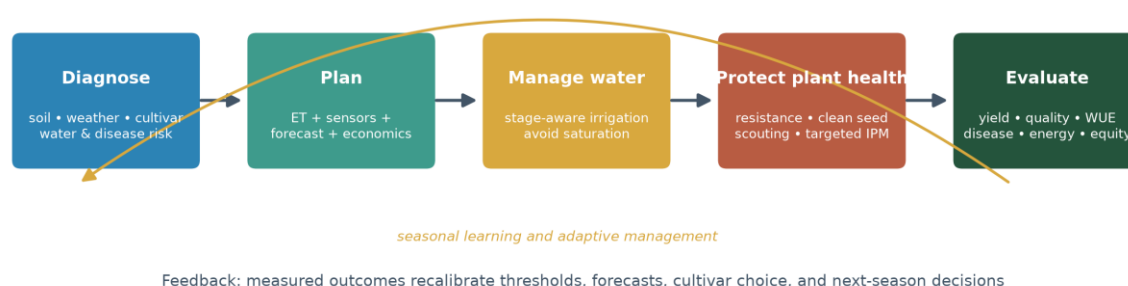


Figure 1. Integrated irrigation-plant-health framework. Source: Author's conceptualization.

Figure 1 is interpreted as a closed-loop system rather than a linear input recipe. Observations include soil moisture, rainfall, crop stage, canopy conditions, disease symptoms, and water quality. Inference translates observations into ET demand, stress status, infection risk, and trade-offs. Actions include irrigation, drainage, nitrogen adjustment, scouting, cultivar choice, sanitation, and justified fungicide use. Evaluation and seasonal feedback prevent a single-season result from being treated as a universal prescription.

Literature Review

Wheat water requirements, ET, and soil-water balance

Wheat water management begins with a water balance, not with a calendar. Crop evapotranspiration is commonly represented as reference evapotranspiration multiplied by a crop coefficient, with adjustments for crop development and evaporation from soil or residue. A practical balance considers effective rainfall, stored soil water, irrigation, runoff, deep percolation, and changes in root-zone storage. FAO guidance recommends combining ET and crop coefficients with soil-water observations and system efficiency; smaller and more frequent applications fit early growth and shallow roots, while larger and less frequent applications can fit mid-season rooting and demand (Rawson & Gómez Macpherson, 2000; Savva & Frenken, 2002).

A water balance is valuable because a soil-moisture reading is not automatically plant-available water. Sensor readings require calibration to texture, bulk density, salinity, installation depth, and root-zone position. Deep-rooted wheat can extract water from multiple layers, and one shallow sensor may trigger irrigation too early or fail to detect deeper saturation. Thresholds should be tied to allowable depletion, crop stage, expected rainfall, drainage, and the objective: maximum yield, yield stability, grain quality, or grain per unit irrigation.

Water productivity is similarly conditional. Yu et al. (2020) synthesized 41 publications and 381 observations and reported that deficit irrigation increased WUE by about 6.6% but reduced yield by about 16.2% on average. The same analysis found more favorable simultaneous yield-WUE outcomes in some dry, loamy or sandy conditions and within its dataset for border or furrow systems. This does not mean surface irrigation is universally superior to pressurized systems. The result is moderated by deficit level, timing, rainfall, soil, temperature, and the denominator used.

Zwart et al. (2010) produced a modeled global benchmark of approximately 0.2–1.8 kg harvestable wheat per m³ of water consumed. This is a spatial benchmark for identifying broad performance gaps, not a field-trial target or a prescription for a particular cultivar. A complete assessment should report absolute water applied and withdrawn, rainfall, soil-water change, ET or consumptive use, runoff and drainage where possible, and the denominator for every efficiency ratio.

Table 1. Key concepts and metrics used in integrated wheat management

Concept or metric	Operational definition or interpretation	Main use	Caution
Crop ET	Evapotranspiration from crop and soil, often estimated from reference ET and crop coefficients	Estimate crop water demand	Model error and crop coefficients vary by stage and canopy
Root-zone soil-water balance	Storage plus rainfall and irrigation minus ET, runoff, and drainage	Schedule irrigation and detect saturation	Requires depth-specific calibration and representative sampling
Crop WUE/WP	Grain yield divided by ET or specified crop water use	Compare biomass/grain return per consumed water	Denominator differs among studies
Irrigation WUE (IWUE)	Yield divided by irrigation water applied	Assess irrigation allocation	Can rise when irrigation is reduced without improving yield or sustainability
Deficit irrigation	Deliberate water application below a full-irrigation reference	Save water or optimize yield–water trade-off	Percentage of full irrigation is not transferable across sites
Supplemental irrigation	Limited irrigation added to rainfall or stored soil water	Stabilize rainfed or partially irrigated wheat	Optimal amount varies with rainfall and stored water
Waterlogging	Root-zone saturation that restricts oxygen and alters nutrient availability	Diagnose excess water stress	Severity depends on duration, soil, genotype, and stage
Disease risk	Combination of host, pathogen/inoculum, environment, and time	Prioritize scouting and treatment	Forecast risk is not disease certainty
Grain health	Yield plus test weight, protein, end-use traits, and DON/toxin status where relevant	Protect food and market quality	Symptom reduction does not guarantee toxin reduction
Sustainability	Yield and quality with water, soil, energy, GHG, economic, and equity outcomes	Evaluate long-term system performance	Efficiency ratios alone are insufficient

Source: Synthesized from Rawson and Gómez Macpherson (2000), Savva and Frenken (2002), Yu et al. (2020), Zwart et al. (2010), and the supplied evidence notes.

Irrigation strategies and crop stage

Deficit and regulated-deficit irrigation

Deficit irrigation is not simply applying less water. Regulated-deficit irrigation places controlled deficits at stages where yield penalties are expected to be smaller and protects high-sensitivity periods. The evidence favors moderation. A China-focused

meta-analysis found that optimized water-saving irrigation reduced irrigation water by 35.1% without a significant overall yield penalty; drip and micro-sprinkler observations showed WUE gains of 18.7% and 10.1%, respectively, while deficits below 40% of full irrigation caused substantial yield loss (Ma et al., 2025). Because the dataset was strongly dominated by drip and micro-sprinkler observations, evidence for other systems was less precise.

A North China Plain furrow experiment compared 60%, 70%, and 80% lower soil-moisture limits. The 70% threshold produced crop water productivity of 1.86 kg m^{-3} under alternate furrow and 1.90 kg m^{-3} under conventional furrow, while higher watering raised yield but lowered WUE (Li et al., 2022). This illustrates that an intermediate threshold may maximize a combined criterion under a particular soil and climate, but it does not establish a universal 70% rule.

Supplemental irrigation

Supplemental irrigation is especially relevant where rainfall is variable rather than absent. An eight-year high-yield study found optimal seasonal supplemental irrigation varied inversely with natural water supply and represented 11–44% of seasonal ET; soil water at sowing, stage-specific precipitation, and crop ET were useful decision variables (Wang, 2017). A two-year winter-wheat trial found moderate jointing irrigation restoring water to field capacity at 20 cm produced the highest yield, WUE, and nitrogen-use efficiency. Restoring water at 40 cm increased nitrogen accumulation without increasing yield, reducing WP and N-use efficiency (Liu et al., 2022).

Drip and micro-sprinkler systems

Drip systems deliver water close to the root zone and permit frequent, adjustable applications, fertigation, and potential reductions in surface evaporation. A China-focused review reported that sub-membrane drip increased wheat yield by 14.6–19.6%, crop WP by 27.3–29.6%, and irrigation WP by 37.1–42.0% in selected cited studies (Yang et al., 2023). The broader meta-analysis found a robust WUE gain but no average drip-yield gain, demonstrating that the comparator, mulch, soil, deficit level, and management matter (Ma et al., 2025). Emitter clogging, filtration, maintenance, capital costs, and management complexity can reverse agronomic advantages.

Micro-sprinkler can provide flexible distribution and moderate water productivity gains. Sprinklers can also create wind drift, evaporation, energy demand, and foliar wetting. These losses and disease effects were not consistently quantified across wheat studies, so “modern” hardware cannot be equated with sustainable outcomes without a full water and energy account.

Furrow irrigation

Furrow irrigation remains important where pressurized systems are unaffordable or unreliable. Its performance depends on land leveling, furrow geometry, inflow, cutback or surge management, infiltration variability, and scheduling thresholds. The 70% lower-limit experiment demonstrates that well-managed furrow irrigation can be competitive on crop WP (Li et al., 2022). A 2025 South Korean study using soil-water-guided furrow irrigation and hydraulic simulation saved approximately 60–110 mm relative to a saturation-based strategy and produced up to 22% higher yield than conventional rainfed management in the reported season (Kim et al., 2025). The study also warns that near-saturation scheduling can cause waterlogging, nutrient leaching, denitrification, and poor root aeration.

Table 2. Irrigation strategies and evidence boundaries

Strategy	Measured or modeled evidence	Best-fit decision context	Principal risks or constraints
Full irrigation	Often protects yield where water is limiting	High-value crop and reliable water supply	Low WP, leaching, energy, canopy humidity, groundwater depletion
Deficit irrigation	Global average: about +6.6% WUE and –16.2% yield versus full irrigation	Water scarcity with explicit yield-risk objective	Severe or poorly timed deficit reduces yield and quality
Regulated deficit	Stage-specific deficits can protect jointing/anthesis while reducing lower-value applications	Calibrated soil, crop stage, rainfall, and yield target	No universal percentage or threshold

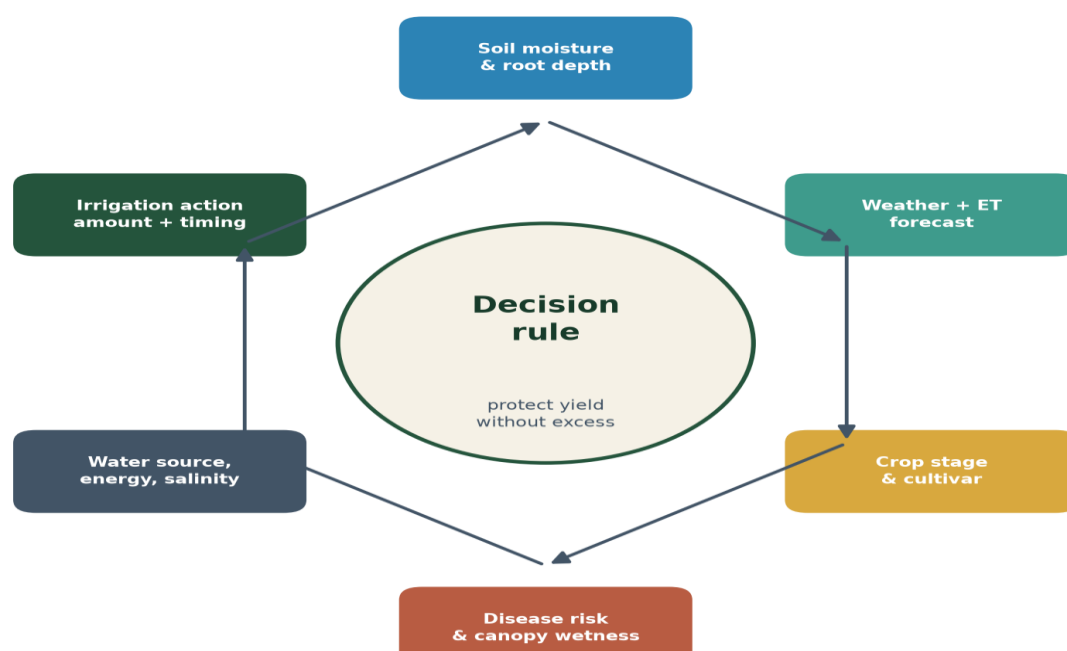
Supplemental irrigation	Optimal seasonal amount varied with rainfall and was 11–44% of ET in one eight-year study	Rainfed/partially irrigated wheat	Transferability across soils and climates
Drip	Selected China studies report high WP gains; meta-analysis reports WUE gain but no average yield gain	High-value fields with filtration, maintenance, and energy	Cost, clogging, skill, embodied materials
Micro-sprinkler	China meta-analysis: +4.1% yield and +10.1% WUE	Flexible, moderate-pressure systems	Wind, evaporation, foliar wetting, energy
Furrow	70% soil-moisture lower limit produced 1.86–1.90 kg m ⁻³ crop WP in one trial	Fields with surface-irrigation infrastructure	Spatial nonuniformity, inlet waterlogging, labor
Sensor/ET scheduling	Zimbabwe wheat trial reported up to 25% water saving while maintaining yield	Farms able to calibrate and maintain sensors	Breakdown, placement, connectivity, false thresholds

Source: Synthesized from Yu et al. (2020), Ma et al. (2025), Li et al. (2022), Kim et al. (2025), Wang (2017), Liu et al. (2022), Munyaradzi et al. (2022), and Yang et al. (2023).

Irrigation scheduling, sensors, and crop stage

FAO scheduling combines reference ET, crop coefficients, effective rainfall, stored soil water, and system efficiency. Soil-moisture sensors provide an observation layer that can verify or correct the modeled balance. Munyaradzi et al. (2022) tested wireless soil-moisture scheduling under drip irrigation in winter wheat in Zimbabwe over three winter seasons. The authors reported up to 25% water saving relative to fixed schedules while maintaining yield and improving irrigation WUE; treatment yields were approximately 3.26 and 3.24 t ha⁻¹ in the reported comparison, with system breakdowns and bird damage as limitations. This is useful direct evidence, but not a universal saving estimate because the study was site-, system-, and sensor-specific.

Jointing/stem elongation is repeatedly identified as a high-value window because stress can reduce leaf area, reproductive capacity, and post-anthesis biomass. Anthesis and early grain filling can be valuable where water supply, yield potential, and disease risk justify it. However, irrigation should not be applied merely because a calendar date has arrived. Before irrigation, a manager should check root-zone water, drainage, crop stage, forecast rainfall, canopy density, disease symptoms, and expected leaf-wetness duration. Avoiding unnecessary overhead wetting before cool, humid periods is a disease-risk recommendation, not a quantified universal treatment effect.

Figure 2. Stage-aware irrigation decision cycle

Source: Author's conceptualization, informed by FAO scheduling guidance and reviewed wheat trials.

Figure 2. Irrigation decision cycle. Source: Author's conceptualization.

Figure 2 emphasizes that a schedule is iterative. A decision may be to irrigate, delay, drain, adjust a threshold, scout, or apply no water. Evaluation includes applied water, soil moisture, crop response, disease observations, and quality—not just whether a pump operated.

Wheat diseases and integrated plant health

Rusts

Stripe/yellow rust, leaf/brown rust, and stem rust are wind-dispersed, polycyclic diseases whose epidemics depend on host susceptibility, pathogen race, temperature, moisture, and crop development. FAO's rust program emphasizes resistant cultivars, certified seed, surveillance, early warning, rapid seed multiplication, emergency planning, and international collaboration. Rust races and virulence patterns change, so resistance is durable only if supported by monitoring and cultivar diversification (Food and Agriculture Organization of the United Nations, n.d.; Rehman et al., 2024).

Carmona et al. (2020) reviewed heterogeneous stripe-rust fungicide trials. Reported yield responses ranged from 13–44% across 40 European trials, 15–23% in Canadian trials, and negative to strongly positive in other locations. The values are study-specific, not expected gains. Two sprays on resistant varieties could have negative economic returns, while one or two sprays on susceptible varieties under high pressure could protect yield. Thus, fungicide decisions should combine inoculum, cultivar susceptibility, weather, yield potential, product efficacy, application timing, and economic return.

Fusarium head blight and DON

FHB is associated with warm, rainy periods around anthesis and abundant residue-derived inoculum. It can produce shriveled kernels, yield loss, and DON contamination. Alisaac and Mahlein (2023) report that severe disease losses can reach 80% in published situations, an upper reported value rather than a normal expectation. Disease management has multiple resistance components, including resistance to initial infection, spread within the spike, kernel infection, and toxin effects.

Rotation and residue management can reduce inoculum, but reduced tillage and wheat-after-maize sequences can increase risk in some systems. Moderately resistant cultivars combined with appropriately timed anthesis fungicide applications are generally more effective for disease and DON management than either alone; triazoles have often outperformed older options in the reviewed North American context, but efficacy varies with timing, head coverage, cultivar, year, disease intensity, and rain (Wegulo et al., 2013). A fungicide that reduces symptoms does not guarantee proportional DON reduction. FHB forecasts predict risk, not certainty, and grain testing remains important where toxin standards and markets require it.

Septoria tritici blotch

Septoria tritici blotch (STB), caused by *Zymoseptoria tritici*, begins on lower leaves and moves upward through repeated infection cycles under cool, wet conditions and rain splash. The Crop Protection Network recommends less-susceptible varieties, rotation away from wheat, residue decomposition, scouting, and weather-informed fungicide decisions (Crop Protection Network, 2019). El Jarroudi et al. (2022) found that upper-leaf severity at soft dough was influenced by lower-leaf disease at L3 emergence and accumulated temperature from stem elongation to mid-flowering across seven seasons and four Luxembourg sites. This is an observational/modeling result rather than an irrigation experiment, but it supports lower-canopy scouting combined with weather information.

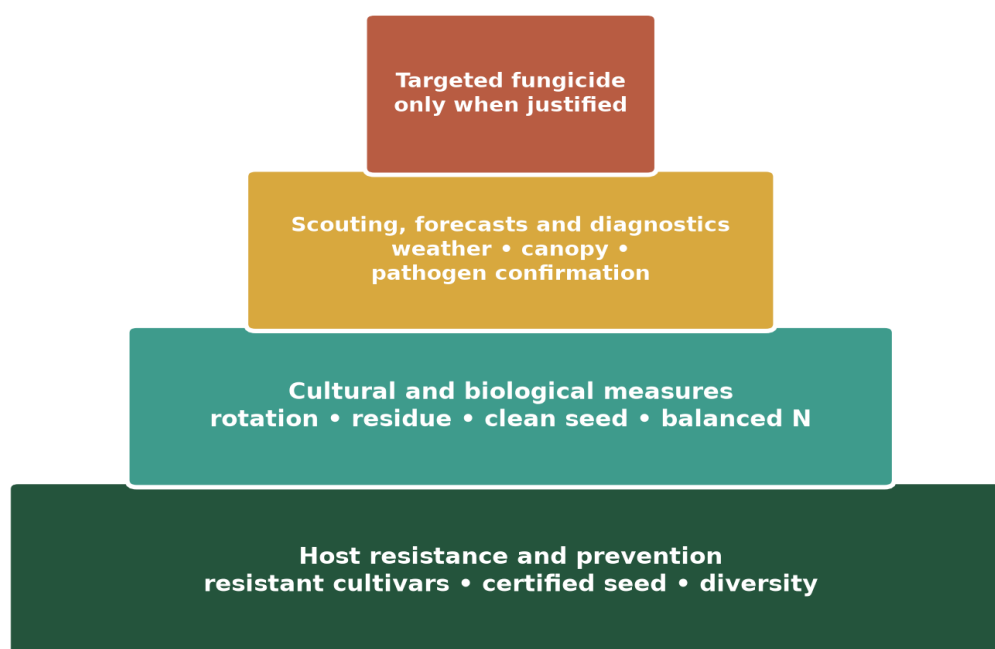
Powdery mildew

Powdery mildew reduces green leaf area and photosynthesis. Published estimates range roughly from 5–40% yield reduction in affected situations, with higher losses under severe infection, while extension guidance reports lower typical losses and strong dependence on cultivar, timing, and location (Singh et al., 2023). Excessive nitrogen, dense stands, and humid canopies can favor mildew. Resistance is preferred, and disease-specific products should be used early when justified. Avoiding excess water and nitrogen is a canopy-management inference, not a substitute for scouting.

Seed-borne diseases

Common bunt, loose smut, and seed-associated Fusarium can impair establishment, yield, and grain quality. Certified or pathogen-tested seed, clean seed handling, uniform seed treatment, resistant varieties, and rotation are central. Seed treatments do not control every problem: the University of Nebraska–Lincoln guidance notes that treatments are not effective for ergot and black chaff, which require pathogen-free seed and other preventive measures (Wegulo, 2017). Labels and allowable active ingredients differ by country.

Figure 3. Integrated disease-management hierarchy for wheat



Evidence principle: prevention and resistance first; chemistry is a conditional layer, not the foundation.

Figure 3. Disease-management hierarchy. Source: Author's conceptualization.

Figure 3 is interpreted as an order of prevention and escalation. Resistant seed and sanitation reduce baseline risk; rotation, residue management, balanced nitrogen, and canopy management reduce favorable conditions; scouting and forecasts identify risk; fungicides are targeted actions; grain testing and harvest segregation protect food quality. Biological control is promising but should be treated as a locally validated adjunct because field efficacy and shelf life vary.

Table 3. Wheat disease-management comparison

Disease group	Key risk conditions	Highest-confidence management components	Irrigation and quality implications
Stripe, leaf, and stem rusts	Susceptible host, favorable temperature/moisture, windborne inoculum, virulent races	Resistant/adapted cultivars, surveillance, scouting, early warning, targeted fungicide	Avoid lush canopies from excess N/water; protect flag leaf and yield potential
FHB/scab and DON	Warm, rainy anthesis, cereal residue, susceptible cultivar, inoculum	Moderately resistant cultivar, rotation/residue management, anthesis forecast, registered fungicide, grain testing	Avoid nonessential wetting around anthesis; symptom control does not assure DON control
Septoria tritici blotch	Cool wet weather, rain splash, lower-leaf inoculum, wheat residue	Less-susceptible variety, rotation, residue decomposition, scouting, forecast-informed spray	Prolonged leaf wetness can increase risk; upper-leaf protection affects grain filling
Powdery mildew	Dense humid canopy, excessive N, susceptible variety, favorable temperatures	Resistant variety, balanced N, canopy management, early targeted product	Avoid excessive water and N that increase humidity and succulence
Common bunt/loose smut/Fusarium seed infection	Contaminated or infected seed, poor establishment hygiene	Certified/pathogen-tested seed, uniform seed treatment, resistant cultivar, rotation	Protect stand, grain odor/quality, and market acceptance
Biological-control options	Agent–environment–pathogen compatibility	Validated microbial products as adjuncts	Do not substitute unvalidated products for resistance and sanitation

Source: Synthesized from Figueroa et al. (2018), Carmona et al. (2020), Alisaac and Mahlein (2023), Wegulo et al. (2013, 2017), Singh et al. (2023), Crop Protection Network (2019), and Food and Agriculture Organization of the United Nations (n.d.).

Irrigation × canopy humidity × nitrogen × disease

Irrigation has two opposing pathways. Better water status can preserve tillers, green leaf area, photosynthesis, and grain filling, thereby increasing yield capacity and sometimes reducing disease-associated stress. Conversely, excessive irrigation, overhead wetting, poor drainage, and high nitrogen can increase canopy density, relative humidity, and leaf-wetness duration. The net response is pathogen-, cultivar-, season-, irrigation-method-, and canopy-dependent.

Marano et al. (2012) compared dry, controlled-deficit, and total sprinkler irrigation in field and greenhouse wheat experiments. Supplemental irrigation increased yield without increasing foliar disease incidence or severity in their experiments; irrigated plants sometimes had lower disease burden. This contrasts with Olesen et al. (2000), whose two-year irrigation × nitrogen × fungicide experiment found that irrigation increased yield but also increased mildew, while higher nitrogen increased mildew in one year. Disease reduced yield mainly through lower harvest index and grain weight. The studies are not contradictory: they differ in environment, cultivar, disease pressure, nitrogen, canopy structure, and irrigation timing.

Sun et al. (2020) reviewed 132 papers and found nitrogen increased disease in 40 cases, decreased it in 25, and had no or variable effects in eight studies using unspecified forms; ammonium and nitrate could differ. Nitrogen can create succulent

tissue and dense canopies that favor pathogens, but can also support defense enzymes and proteins. Therefore, “more N” is neither disease-neutral nor universally disease-promoting.

Waterlogging is a distinct excess-water stress. Saturation restricts oxygen diffusion, changes nutrient and micronutrient availability, and damages roots. Setter et al. (2009) reported approximately 10%, 25%, and 65% grain-yield reductions under low, moderate, and severe waterlogging in a multi-location screening context, with unstable genotype rankings across soils. These figures are reported screening results, not universal cultivar penalties.

Table 4. Irrigation–canopy–nitrogen–disease interactions

Interaction pathway	Potential benefit	Potential harm	Management interpretation
Water status × disease	Preserves leaf area, tillers, and grain filling; may improve tolerance	Does not prevent infection; can increase canopy density	Maintain adequate water while using IPM; do not impose drought as disease control
Overhead irrigation × leaf wetness	Rapidly supplies water	Prolongs wetness and can favor foliar pathogens	Time applications for drying conditions and avoid unnecessary wetting
Excess irrigation × drainage	Reduces drought risk	Saturation, leaching, denitrification, root hypoxia, waterlogging	Measure soil water and drainage; stop irrigation on saturated profiles
Nitrogen × canopy	Supports yield and protein under adequate water	Succulent, dense canopy and increased mildew/rust risk in some cases	Match N to yield potential, mineral N, water availability, and canopy observations
Jointing water × yield formation	Protects reproductive growth and post-anthesis biomass	Over-application lowers WP and can increase N movement	Prioritize with calibrated thresholds rather than a fixed volume
Anthesis water × grain quality/disease	Supports flowering and grain set where needed	Warm, rainy wetness can raise FHB/DON risk	Integrate forecast, cultivar, residue risk, and fungicide timing
Salinity × irrigation	Leaching may reduce salts if drainage exists	Poor-quality water and inadequate drainage increase salinity	Test water/soil EC and ensure drainage before leaching

Source: Synthesized from Marano et al. (2012), Olesen et al. (2000), Sun et al. (2020), Setter et al. (2009), Alisaac and Mahlein (2023), Si et al. (2023), and Yonts et al. (n.d.).

Soil health, salinity, waterlogging, energy, GHGs, and climate resilience

Conservation agriculture can buffer soil temperature and water stress, but outcomes are context-dependent. In an eight-year warming experiment in the North China Plain, conservation agriculture with permanent residue cover and no tillage produced cooler, wetter soils, a 21% average increase across 17 soil-health indicators, and a 9.3% wheat-yield increase associated with warming-triggered microbial changes under conservation agriculture (Teng et al., 2024). This is a long-term single-site experiment and cannot establish universal transferability. Residue availability, weed control, equipment, rotation, nutrient management, and transition costs matter.

A global synthesis reported an average 11% reduction in soil N₂O emissions under no-till or reduced tillage, but cover-crop and rotation effects varied with pH, soil carbon and nitrogen, climate, and region (Li et al., 2023). Total GHG performance also includes pumping energy, fertilizer, machinery, possible CH₄ changes, and soil-carbon permanence. Irrigation energy depends on water source, lift, pump efficiency, conveyance, electricity or diesel, and whether saved water expands irrigated area.

Salinity is especially important in Pakistan and other irrigated regions. Salinity reduces germination, growth, reproduction, yield, and grain quality through osmotic stress and ion toxicity. Integrated responses include drainage, salt leaching where hydrologically feasible, water-quality monitoring, nutrient management, establishment practices, seed priming, and breeding (El Sabagh et al., 2021). Leaching without drainage can move salts rather than solve the root-zone problem.

Climate-model evidence supports adaptation packages rather than single traits. Pequeno et al. (2021) projected a global wheat-production decline of 1.9% under their model ensemble and larger average declines in Africa and South Asia by mid-century under RCP8.5; traits such as heat tolerance, early vigor, and later flowering improved yields in many simulations but were limited by water and nitrogen stress. These are model projections, not observed future outcomes, and do not fully represent flooding or disease.

Digital agriculture, sensing, AI/ML, forecasting, and VRI

A useful digital architecture has three layers: observations, inference, and action. Observations include soil moisture, weather, canopy temperature, reflectance, leaf wetness, and disease symptoms. Inference includes ET or water-stress estimation, infection-risk models, and ML predictions. Actions include irrigation timing and rate, variable-rate irrigation (VRI), scouting, fungicide decisions, and drainage.

Remote sensing is biologically relevant but indirect. Optical indices can indicate vegetation condition; thermal approaches can indicate canopy water stress; ET products can support crop-water estimates; satellite imagery offers spatial coverage; UAVs offer fine resolution (Sishodia et al., 2020; Neupane & Baysal-Gurel, 2021). Stress, nitrogen deficiency, senescence, and disease can produce overlapping signatures, so imagery should prioritize scouting rather than replace ground confirmation.

Li et al. (2022) used UAV hyperspectral data and ensemble ML for winter-wheat yield prediction. Base-model R^2 values were 0.62–0.73 and the reported ensemble maximum was 0.78 at grain filling. This demonstrates within-study prediction, not a measured yield increase from using the model and not external validation across cultivars, seasons, or regions.

Weather-based disease forecasting can be more interpretable. El Jarroudi et al. (2017) developed a winter-wheat stripe-rust threshold model in Luxembourg using temperature, relative humidity, rainfall, and favorable-weather duration. The reported probability of detection was at least 0.90, average false-alarm ratio no more than 0.38, and critical success index 0.63–1. These are strong model results in a specific geography and period. Local recalibration is required before transfer to Pakistan or another region.

VRI evidence must be bounded. Sui and Yan (2017) tested center-pivot VRI in soybean and corn, not wheat, and reported 25% less water, small yield gains, and higher water productivity. The study supports engineering plausibility but not wheat-specific yield, disease, or profitability claims. A wheat VRI trial should measure water applied and consumed, grain yield, protein, test weight, disease, energy, gross margin, and groundwater consequences against uniform-rate and farmer practice.

Table 5. Digital tools, evidence strength, and operational requirements

Tool	Demonstrated evidence	Evidence boundary	Operational requirement
Soil-moisture IoT	Zimbabwe wheat trial reported up to 25% water saving with maintained yield	Site and sensor specific; breakdowns occurred	Calibration, multiple depths, representative placement, fallback schedule
ET/weather balance	FAO-supported scheduling framework	Requires coefficients, rainfall, and efficiency estimates	Local weather and soil data; audit applied water
Satellite imagery	Large-area monitoring of variability and crop condition	Resolution, clouds, mixed pixels, revisit limits	Fusion with ground data and targeted UAV/scouting
UAV multispectral/hyperspectral	Within-study winter-wheat yield prediction; R^2 up to 0.78 in one model	Not proof of management impact or generalization	Ground truth, repeat flights, authorization, skilled processing

Weather rust forecast	Luxembourg model had high detection and useful skill metrics	Geographic and pathogen-system specificity	Recalibration, cultivar and scouting integration
Climate-suitability model	Wheat-blast suitability mapped in Asia	Suitability is not outbreak prediction	Surveillance and preparedness, not automatic treatment
VRI	25% less water and WP gains in corn/soybean	Wheat outcomes unverified in that study	Wheat-specific prescriptions, hydraulic uniformity, economics
AI/ML disease diagnosis	Reviews and datasets show classification potential	Accuracy may not translate to field decisions	Independent site/season validation, uncertainty, explainability

Source: Synthesized from Munyaradzi et al. (2022), Sishodia et al. (2020), Li et al. (2022), El Jarroudi et al. (2017), Montes et al. (2022), Sui and Yan (2017), Neupane and Baysal-Gurel (2021), and Pathmudi et al. (2023).

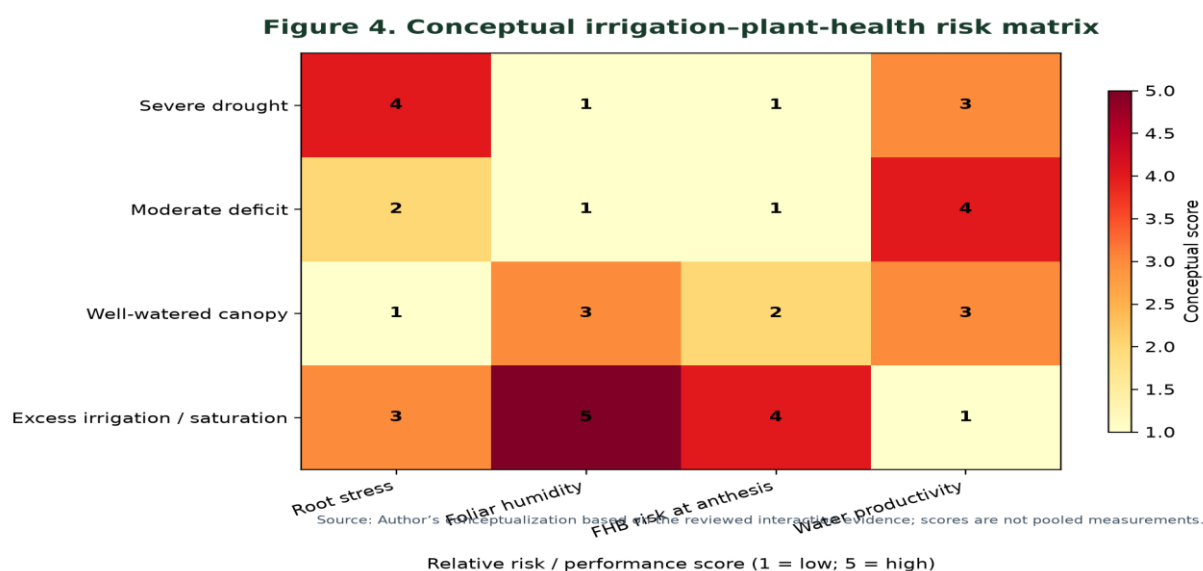


Figure 4. Irrigation-disease interaction matrix. Source: Author's conceptualization based on the reviewed evidence.

Figure 4 should be read as a risk map, not as a set of universal treatment effects. Adequate root-zone water at jointing is generally beneficial for yield formation; unnecessary canopy wetting at anthesis under warm, rainy conditions is potentially risky for FHB; and irrigation into a saturated profile is harmful through waterlogging even if disease is absent.

Research Methodology

Design

The paper uses a qualitative systematic/narrative literature-review methodology. "Systematic" refers to structured scope, explicit evidence discipline, source verification, categorization, and comparison. "Narrative" refers to synthesis across heterogeneous study designs and outcomes where statistical pooling is inappropriate. This is not a de novo meta-analysis and does not claim PRISMA counts. No new field measurements, experiments, database searches, or causal estimates were conducted for this manuscript.

Source base and source types

The source base consisted of the supplied research-note files and their verified source details. The notes covered five interlocking domains: irrigation and water productivity; disease management; irrigation-disease interactions; sustainability and climate resilience; precision agriculture and digital decision support; and Pakistan/developing-economy context. Source

types included peer-reviewed meta-analyses, field and greenhouse experiments, multi-season observational or surveillance studies, crop and climate models, reviews, FAO technical guidance, government and World Bank reports, extension publications, and operational advisory systems.

The hierarchy was functional rather than absolute. Meta-analyses and replicated field experiments were used for comparative measured effects. Observational disease surveillance was used to describe spatial and temporal patterns, not causality. Models were used to evaluate scenarios and decision-support potential, not to represent observed national outcomes. FAO and extension material was used for operational principles and definitions. Official statistics and policy reports were used for context while documenting their definitions and methodological limits.

Inclusion logic

A source was included when it was present in the verified notes, had identifiable authorship or institutional authorship, and directly informed at least one objective or research question. Priority was given to wheat-specific evidence, recent sources from 2020–2026, quantitative syntheses, multi-season research, and sources with clear methods and boundaries. Older seminal sources were retained when they supplied foundational irrigation guidance, irrigation × nitrogen × fungicide evidence, waterlogging evidence, or established disease-management concepts.

Sources were included for different claim types: measured results, modeled results, observational associations, recommendations, and conceptual architecture. A source did not need to be an experiment to be useful, but the claim was labeled according to the source design. For example, a Pakistan DSSAT study supports a modeled site scenario, while a leaf-rust survey supports spatial surveillance evidence. Neither supports a causal national prescription.

Exclusion logic

The paper excluded unsupported claims, invented sources, unverified DOI numbers, unreported experiments, and statistics not present in the notes. It excluded internal source labels from the final manuscript. It did not combine effect sizes across studies with incompatible denominators, deficit definitions, soils, climates, or comparators. It excluded a retracted irrigation-energy estimate noted in the sustainability materials. It did not treat a model's prediction accuracy as proof of management impact, nor a policy report's cross-country comparison as an estimate of a single intervention.

Evidence extraction

Evidence was extracted into five fields: (1) intervention or exposure; (2) outcome and metric; (3) design and setting; (4) result or recommendation; and (5) limitation or transfer boundary. Irrigation studies were coded for method, deficit definition, growth stage, water denominator, yield, WUE/WP, quality, and nitrogen. Disease studies were coded for pathogen, host resistance, inoculum, canopy or weather condition, disease outcome, grain-health outcome, and fungicide timing. Sustainability studies were coded for soil health, salinity, waterlogging, energy, GHGs, quality, profitability, and equity. Digital studies were coded for observation, model, action, validation design, and adoption requirement. Pakistan sources were coded for official statistic, field observation, model, policy diagnosis, or adoption association.

Synthesis procedure

The synthesis proceeded in four stages. First, concepts and denominators were harmonized, especially crop WP, IWUE, ET, irrigation water, and total water use. Second, evidence was compared within domains, such as deficit versus optimized water-saving irrigation or resistance versus fungicide. Third, cross-domain mechanisms were synthesized, focusing on crop stage, canopy humidity, nitrogen, root-zone saturation, salinity, and disease. Fourth, a decision framework was developed that connects observation, inference, action, evaluation, and seasonal learning.

Contradictions were treated as evidence of moderation rather than as errors when study designs differed. For example, global deficit irrigation reduced average yield while China-focused optimized water-saving irrigation showed no overall yield penalty; these outcomes can coexist because the interventions, definitions, climates, and datasets differ. Similarly, irrigation reduced disease burden in one study and increased mildew in another because canopy, nitrogen, pathogen, and environment differed.

Quality and caution rules

The following rules governed interpretation:

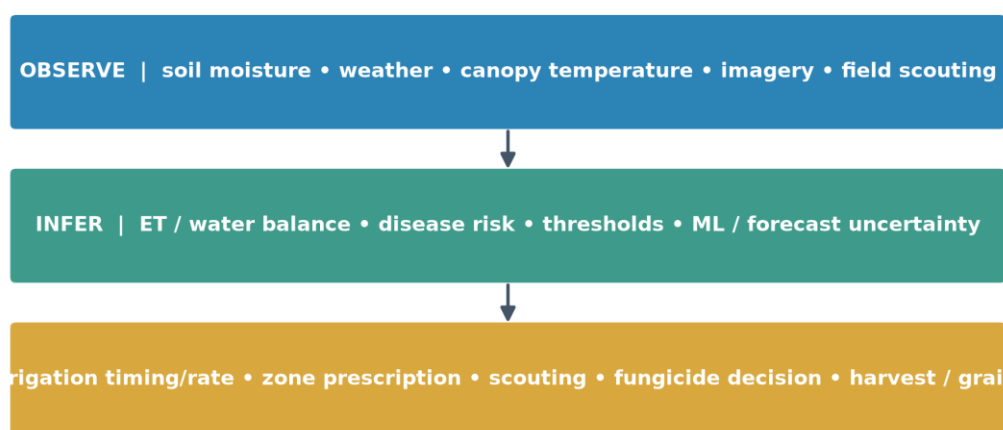
1. Report study-specific numerical outcomes with study context.
2. Distinguish measured, modeled, observational, recommended, and conceptual claims.

3. Do not convert modeled or observational results into causal national prescriptions.
4. State the denominator for water productivity and note whether rainfall is included.
5. Treat official statistics as definition-dependent and reconcile discrepancies before quotation.
6. Treat disease forecasts as risk information, not certainty or automatic fungicide instructions.
7. Treat AI/ML accuracy as model performance, not farm benefit.
8. Treat extension guidance as operationally useful but not equivalent to controlled experimentation.
9. Prefer bundles and locally calibrated thresholds over single-technology claims.

Limitations of the methodology

Because the review uses supplied notes rather than a newly executed database search, it cannot claim exhaustive retrieval. The evidence base is geographically concentrated in China, Europe, Australia, Zimbabwe, North America, and selected Pakistan studies. Direct irrigation × disease × nitrogen factorial experiments are rare. Water-productivity denominators and deficit definitions vary. Many studies report yield but not grain quality, mycotoxin, energy, GHG, or adoption outcomes. Pakistan official statistics and program documents use different definitions and measurement procedures. These limitations constrain generalization and justify the cautious, framework-oriented conclusions.

Figure 5. Digital decision-support architecture for integrated wheat management



Human-in-the-loop validation: calibrate locally, inspect fields, record outcomes, and fall back safely when data fail.

Figure 5. Digital decision architecture. Source: Author's conceptualization.

Figure 5 is interpreted as a human-in-the-loop system. Sensors and models inform, but do not replace, agronomic judgment, field scouting, label compliance, or farmer knowledge. A robust architecture has calibration, uncertainty, connectivity fallback, and an explicit action record so that seasonal learning is possible.

Results, Analysis and Discussion

Result 1: A stage-aware, threshold-aware water strategy is more defensible than a universal irrigation recipe

The first review result answers Objective 1 and Research Question 1. Wheat water management should combine ET demand, effective rainfall, stored soil water, root-zone depth, crop stage, soil texture, drainage, and system capability. The recurring stage signal is jointing/stem elongation as a high-value stress-avoidance window. Anthesis and early grain filling can also be important, particularly where yield potential and water availability justify them. The evidence does not support a fixed number of irrigations, a universal percentage of ETc, or a universal soil-moisture threshold.

This result follows from converging but heterogeneous evidence. The eight-year supplemental-irrigation study linked optimal irrigation amount to natural water supply and post-jointing demand (Wang, 2017). The jointing trial found that moderate restoration at 20 cm outperformed deeper restoration for combined yield, WP, and N-use efficiency (Liu et al., 2022). The furrow trial identified a moderate threshold as a compromise between yield and WP (Li et al., 2022). FAO guidance supplies a

transferable decision logic—ET plus soil-water balance—rather than a single threshold (Rawson & Gómez Macpherson, 2000; Savva & Frenken, 2002).

The analytical implication is that timing and diagnosis are at least as important as hardware. A low-cost furrow system with good leveling, soil-water observation, and drainage can outperform a poorly maintained pressurized system. Drip can provide fine control but requires filtration, maintenance, energy, and skilled scheduling. Sensor technology can improve decisions only if placement and calibration represent the field.

Result 2: Moderate water saving can improve WP, but yield and quality risk rises with severe or poorly timed deficit

This result answers Objective 2 and Research Question 2. Evidence supports a conditional rather than absolute proposition: moderate deficit or optimized water-saving irrigation can improve water productivity, while severe deficit commonly reduces yield and may reduce nutrient uptake and grain quality. Yu et al. (2020) reported a global average trade-off of higher WUE and lower yield under deficit irrigation. Ma et al. (2025) reported reduced irrigation water without overall yield penalty for optimized water-saving irrigation in China, with substantial losses under deficits below 40% of full irrigation. The difference is explainable by intervention definition, dataset composition, climate, soil, method, timing, and denominators.

The sustainability interpretation is important. A higher IWUE can result from applying less water while yield remains constant, but a higher crop WUE can coexist with lower grain yield if ET declines. Therefore, recommendations must state the objective: stabilize yield, maximize grain per unit irrigation, maximize grain per unit ET, preserve protein and baking quality, or maximize profit. These objectives can choose different schedules.

Grain quality complicates the yield story. Si et al. (2023) synthesized evidence that irrigation amount and timing influence dough stability and quality, while Zhang et al. (2017) showed interactions among irrigation and nitrogen in grain amino-acid composition and protein quality. A three-season North China Plain study found jointing and jointing-plus-anthesis irrigation increased yield by 12.79% and 18.65% relative to no irrigation, respectively, without a significant protein change in the reported seasons but with changes in amino-acid indices (Zhang et al., 2017). These high-yield-site results do not establish a universal prescription.

The Pakistan field study provides a useful local boundary. Under 100%, 80%, 60%, and 40% ETc in a semi-arid setting, biomass fell by 8%, 23%, and 48%, and grain yield fell by 7%, 23%, and 50% relative to full irrigation; WUE remained statistically similar at 100–60% ETc and fell sharply at 40% (Hafiza et al., 2025). The authors identify 80% ETc as a possible water-saving level for that setting. It should not be transferred to all Pakistan locations, soils, cultivars, or irrigation systems.

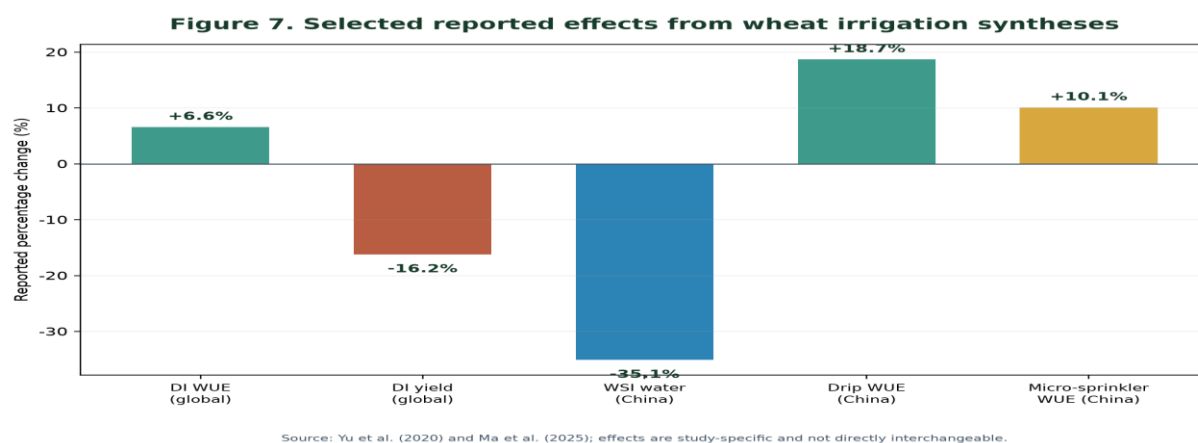


Figure 7. Reported irrigation effects. Source: Quantitative values are attributed in the accompanying text to Yu et al. (2020), Ma et al. (2025), Liu et al. (2022), Wang (2017), Hafiza et al. (2025), and Munyaradzi et al. (2022); figure design and synthesis are the author's.

Figure 7 must be interpreted as a comparison of reported study outcomes, not as a pooled meta-analysis. Its central message is variation: the same word—“deficit”—can describe very different water amounts, timings, thresholds, soils, and objectives.

Result 3: Plant-health protection is a hierarchy, with resistance and clean seed before chemistry

This result answers Objective 3 and Research Question 3. The literature converges on a practical disease-management hierarchy: locally adapted resistant or less-susceptible cultivar; certified and clean seed with appropriate treatment; rotation,

residue and volunteer management; balanced canopy and nitrogen; scouting and weather information; validated forecasting; and registered fungicide only when risk, crop value, efficacy, timing, and economics justify it.

The hierarchy is strongest for rusts, where FAO emphasizes resistant cultivars, surveillance, seed multiplication, and early warning. However, rust resistance can be overcome, making diversity and monitoring necessary. FHB requires an explicit grain-health endpoint. Moderately resistant cultivars and anthesis-timed fungicide are more effective together than alone, but DON reduction is not guaranteed. STB management requires lower-canopy scouting because early disease and accumulated weather conditions help predict upper-leaf severity. Powdery mildew management requires attention to cultivar, nitrogen, canopy density, and early targeted action. Seed-borne disease prevention begins before planting.

Fungicide stewardship is both agronomic and evolutionary. Routine calendar sprays can impose cost and selection pressure without adequate return. Products, modes of action, rates, and timing must follow local labels and resistance-management guidance. The evidence does not support a generic fungicide program detached from cultivar resistance, disease pressure, or weather.

Result 4: Irrigation, nitrogen, and disease outcomes are non-monotonic and must be co-managed

This result answers Objective 4 and Research Question 4. The net effect of irrigation on disease is not “more water equals more disease.” In Marano et al. (2012), supplemental irrigation increased yield without increasing foliar disease. In Olesen et al. (2000), irrigation increased mildew and nitrogen increased mildew in one year, while yield benefits depended on disease and nitrogen. These findings support a conditional model: water improves crop vigor when drought is limiting but can increase canopy humidity and succulence when water and nitrogen exceed crop demand.

FHB illustrates a different interaction. Warm, rainy anthesis conditions and residue inoculum create risk, while irrigation is only one source of wetness. The defensible recommendation is to avoid nonessential canopy wetting during high-risk conditions, intensify scouting and forecasting, and align fungicide decisions with cultivar and pathogen risk. This is an epidemiology-based inference, not a universal irrigation cutoff.

Waterlogging is a plant-health and soil-health problem distinct from leaf wetness. Saturated soil reduces oxygen and changes nutrient dynamics; yield penalties can be large and genotype rankings unstable. Drainage and rapid correction of ponding are therefore as important as the choice of irrigation method. Salinity requires water-quality and soil-EC diagnosis before recommending additional irrigation or leaching.

Table 6. Evidence-synthesis matrix by claim type

Claim	Evidence type	What can be stated	What cannot be stated
Deficit irrigation raises WUE but may lower yield	Global meta-analysis	Conditional average trade-off	A universal deficit percentage
Optimized water-saving irrigation can save water without yield penalty	China meta-analysis	Dataset-level average under defined systems	Transferable outcome for every country or method
Wireless sensors can save water in wheat	Three-season experiment	Site-specific measured evidence	Universal 25% saving or automatic profitability
80% ETc may be suitable in semi-arid Pakistan	Local field experiment	A possible local candidate	National recommendation
Reduced irrigation may increase yield in semi-arid Pakistan sites	DSSAT simulation	Scenario/model result	Causal farmer-field effect
Leaf rust hotspots vary in Pakistan	Three-year surveillance	Spatial targeting and monitoring need	Unbiased national prevalence or causal climate effect
Adaptation adoption correlates with welfare	Observational sectional study	Association after matching on observables	Causal effect of integrated irrigation-disease packages

UAV ML predicts winter-wheat yield	Within-study model	Predictive performance in tested data	Farm-level yield gain or external validity
Weather model predicts stripe-rust risk	Regional model	Decision-support potential	Unchanged thresholds in Pakistan
VRI improves WP in corn/soybean	Field experiment in other crops	Engineering plausibility	Wheat-specific disease, yield, or profit effect

Source: Author's synthesis of verified evidence from the supplied research notes.

Result 5: Sustainability is a multi-accounting problem

This result answers Objectives 2, 4, and 6. Sustainable wheat cannot be assessed by yield or WUE alone. The relevant accounting includes water withdrawals and consumptive use, soil moisture and drainage, salinity, nitrogen movement, pumping energy, GHGs, soil organic carbon, grain quality, profitability, and equity. More irrigation can stabilize yield but increase pumping and leaching. Pressurized irrigation can improve application control but require energy and maintenance. Conservation agriculture can improve soil health and buffer warming but depends on residue, weed, equipment, and nutrient conditions. Reduced tillage has a relatively consistent N₂O reduction signal in one global synthesis, but total GHG outcomes require broader boundaries (Li et al., 2023).

The SDG implications are direct. SDG 2 requires reliable, quality grain; SDG 6 requires sustainable water use and groundwater governance; SDG 7 concerns energy for pumping; SDG 12 concerns input efficiency; SDG 13 concerns adaptation and emissions; and SDG 15 concerns soils, erosion, and biodiversity. FAO emphasizes that efficient irrigation must be equitable and governed, because technology can increase extraction or exclude smallholders if water rights, data, and finance are not addressed (Food and Agriculture Organization of the United Nations, 2020a, 2020b).

Result 6: Digital tools close a decision loop only when linked to action and validation

This result answers Objective 5 and Research Question 5. Digital evidence is strongest where a tool is connected to a measured agronomic action. Wireless soil-moisture scheduling in Zimbabwe is one example. Weather-based stripe-rust modeling is another. In contrast, UAV yield prediction, climate-suitability mapping, and VRI evidence from non-wheat crops support plausibility or prediction, not demonstrated wheat management outcomes.

A reliable digital service should have: representative sensors; calibrated thresholds; weather and crop-stage data; disease scouting; interpretable uncertainty; a human decision-maker; an action log; and fallback procedures for power, connectivity, or sensor failure. AI/ML should be externally validated by site and season, report uncertainty and class balance, and demonstrate that predictions improve irrigation, fungicide use, water productivity, grain quality, or profit. Without those tests, digital agriculture remains a promising infrastructure rather than a proven outcome.

Result 7: Pakistan requires a serviceable, locally calibrated bundle

This result answers Objective 6 and Research Question 6. Pakistan is not one irrigation or disease environment. The official agricultural statistics system reports approximately 10.0 million ha and 30.0 million tonnes of wheat for 2023–24 in one summary table, while a separate detailed variety-wise table reports 9,734.8 thousand ha and 31,814.5 thousand tonnes. The discrepancy should be flagged as a table-definition or rounding issue and reconciled before selecting a value; it should not be silently averaged (Ministry of National Food Security and Research, 2024). Pakistan Bureau of Statistics also describes heterogeneous estimation procedures, including crop-cutting surveys in Punjab and Sindh and other procedures in other stages or provinces.

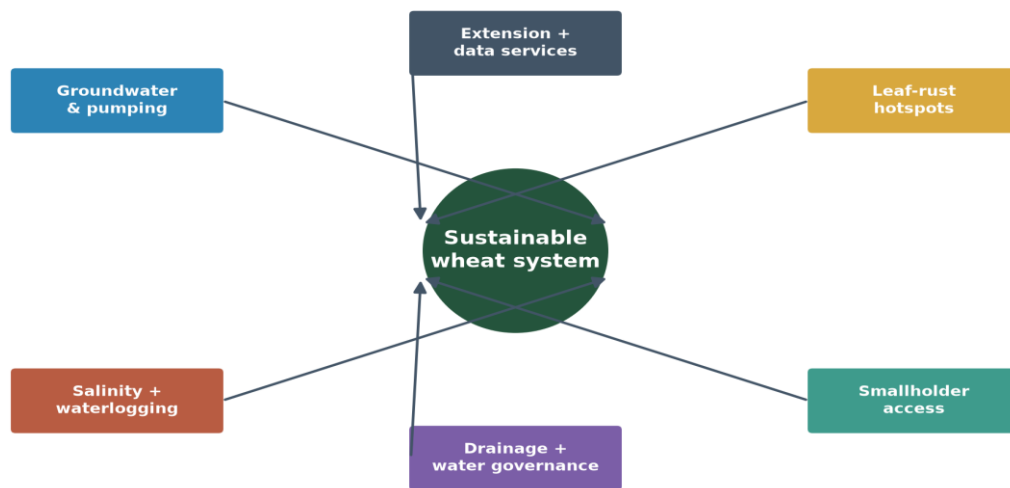
Pakistan's water constraints include groundwater dependence, localized depletion, waterlogging, salinity, conveyance losses, and weak groundwater regulation. The World Bank reports broad productivity gaps and identifies waterlogging, drainage, crop mix, water losses, and groundwater control as contributing factors (Young et al., 2019). A 2023 policy note reports low agricultural water productivity relative to selected countries and broad waterlogging and salinity indicators; these are policy-report comparisons rather than causal evidence for a single technology (World Bank, 2023). ACIAR reports large salinity concerns and institutional challenges but notes should be checked against underlying measurement sources (Australian Centre for International Agricultural Research, 2022).

The Pakistan DSSAT study demonstrates why local calibration matters. In an arid site, modeled yield declined as irrigation was reduced; in two semi-arid sites, modeled yield and WUE were higher under 40–50% less irrigation than the modeled baseline. These are simulations with fixed timing and no joint salinity, disease, energy, labor, or adoption model (Jabeen et al., 2022). They cannot be generalized as national prescriptions.

Pakistan leaf-rust surveillance found stronger and more variable pressure in Sindh and Punjab than in northern cold wheat regions, with changing field coverage across years. Severe infestation occurred in a subset of Sindh fields, while leaf rust was absent from more than 95% of surveyed Punjab fields in the reported surveillance context. These percentages are not unbiased national prevalence estimates because the survey was not a fixed longitudinal panel (Khan et al., 2021). They do support differentiated surveillance and resistance priorities.

Adoption evidence further limits technology-only strategies. Ali and Erenstein (2017) found that more adaptation practices were associated with improved food security and lower poverty after propensity-score matching, but the cross-sectional design cannot eliminate unobserved confounding. Evidence from Bihar shows that awareness, social networks, custom-hire services, and proximity to providers influence zero-tillage adoption among smallholders (Keil et al., 2017). The institutional lesson is relevant to Pakistan: irrigation sensors, disease advisories, and machinery require credit, repair, extension, service markets, and trusted local intermediaries.

Figure 6. Pakistan-relevant systems context for integrated wheat management



Source: Author's conceptualization from Pakistan water, salinity, surveillance and adoption evidence.

Figure 6. Pakistan systems context. Source: Author's conceptualization using Ministry of National Food Security and Research (2024), Young et al. (2019), World Bank (2023), Jabeen et al. (2022), and Khan et al. (2021).

Figure 6 is interpreted as a systems map. Water allocation, water quality, soil condition, crop choice, cultivar, disease surveillance, energy, and service delivery interact. A local package may be more sustainable when it improves scheduling and drainage without requiring unaffordable hardware.

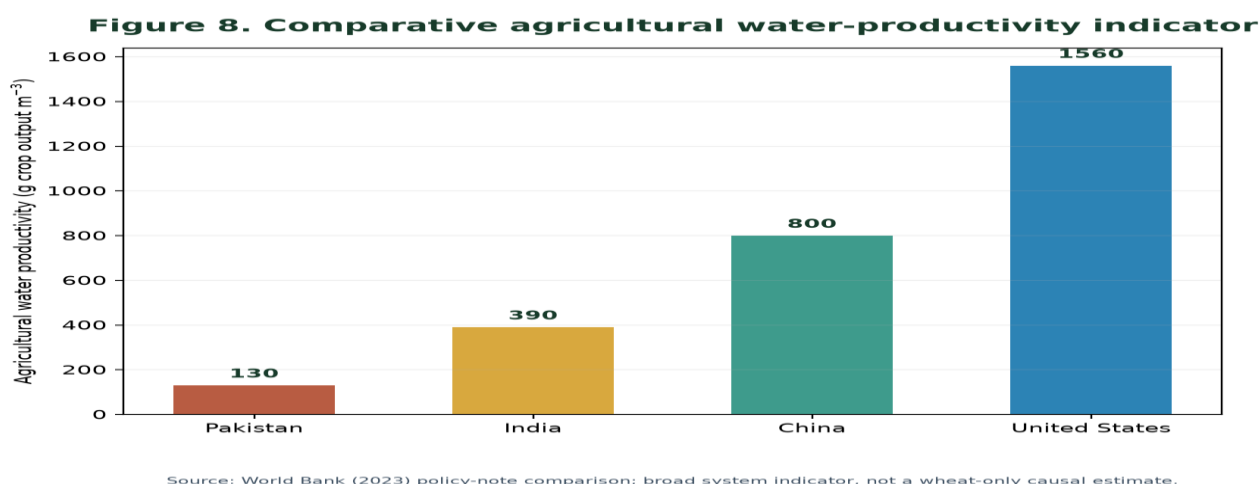


Figure 8. Pakistan water-productivity evidence. Source: Quantitative values are attributed in the accompanying text to Young et al. (2019), World Bank (2023), and Jabeen et al. (2022); figure design and boundary annotations are the author's.

Figure 8 must not be interpreted as a national causal ranking. The cross-country water-productivity comparison is a policy indicator, while the Dera Ghazi Khan values are modeled site scenarios. Together they establish a need for local measurement and governance, not a guaranteed technology effect.

Table 7. Pakistan constraints and locally relevant responses

Constraint	Evidence status	Risk to integrated wheat management	Locally relevant response
Official production-table discrepancy	Verified source-handling issue	Misleading comparisons and targets	Report table definition, reconcile before quotation
Groundwater dependence and weak regulation	Policy/diagnostic evidence	Depletion and rebound after efficiency	Monitoring, transparent allocation, energy/incentive reform
Waterlogging and drainage	Policy/physiological evidence	Root injury, nutrient disorder, yield loss	Drainage assessment, avoid saturated irrigation, tolerant material testing
Salinity and saline groundwater	Program/report and review evidence	Poor establishment, yield and quality loss	EC testing, drainage, salt management, tolerant germplasm
Leaf-rust spatial variability	Three-year surveillance	National average hides hotspots	Sentinel surveillance, resistant seed, regional advisories
Modeled irrigation optima	DSSAT scenario evidence	Model results misread as prescriptions	On-farm validation across soils, seasons, and timings
Smallholder finance and services	Observational/adoption evidence	Sensor, seed, fungicide, and equipment exclusion	Credit, custom hire, repair, extension, social learning
Connectivity and data quality	Digital reviews and trials	False thresholds or missed alerts	Low-bandwidth tools, local calibration, fallback schedules
Energy cost and pump efficiency	Sustainability synthesis	Higher operating cost and GHGs	Measure pumping head, efficiency, source, and energy per tonne

Grain-quality reporting	under-	Cross-domain evidence gap	Yield gains may hide protein/DON losses	Measure test weight, protein, baking traits, DON where relevant
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Source: Author's synthesis of Ministry of National Food Security and Research (2024), Young et al. (2019), World Bank (2023), Australian Centre for International Agricultural Research (2022), Jabeen et al. (2022), Khan et al. (2021), Ali and Erenstein (2017), and Keil et al. (2017).

Integrated framework and explicit answers to objectives and questions

The evidence supports the following integrated cycle:

Diagnose: Measure or estimate ET, rainfall, stored soil water at multiple depths, drainage, salinity, crop stage, cultivar susceptibility, canopy density, nitrogen status, recent disease, residue inoculum, and forecast weather.

Plan: Set the objective—yield stability, irrigation WP, crop WP, quality, profit, or risk reduction—and choose a locally feasible method, threshold, and disease-management hierarchy.

Apply stage-aware irrigation: Protect jointing/stem elongation first under limited water; consider anthesis and early grain filling when justified; avoid severe deficit, unnecessary saturation, and avoidable canopy wetness.

Protect plant health: Use resistant or less-susceptible cultivar, clean treated seed, rotation/residue and volunteer management, balanced nitrogen, scouting, validated forecasts, and targeted registered fungicide.

Evaluate: Record water applied, rainfall, soil-water change, ET, yield, yield components, WP denominator, disease progress, grain quality, DON where relevant, energy, GHG indicators, costs, and labor.

Seasonal feedback: Recalibrate thresholds and recommendations using observed outcomes, disease race information, water quality, equipment reliability, and farmer experience.

This cycle answers all six research questions. Water demand should be diagnosed through ET plus soil-water balance and sensors; moderate water saving is conditional and must be judged against yield and quality; disease protection begins with resistance and sanitation; irrigation and disease are coupled through canopy and nitrogen; digital tools are credible only when linked to validated actions; and Pakistan requires locally calibrated bundles delivered through services and governance rather than technology alone.

Conclusion and Recommendations

Conclusion

This literature review finds that sustainable wheat production is best understood as an integrated water–plant–health–soil–service problem. The evidence does not support a universal irrigation technology, fixed deficit level, or national disease schedule. It supports diagnosis, stage awareness, moderate thresholds, prevention, monitoring, and feedback.

The first conclusion is that irrigation should be scheduled from crop demand and root-zone condition. ET, rainfall, stored soil water, crop stage, drainage, and soil texture must be combined. Jointing/stem elongation is a recurrent high-value stress-avoidance stage; anthesis and grain filling matter where water, yield potential, and disease conditions justify them. Deficit irrigation can improve ratios while reducing yield, whereas optimized water-saving systems can reduce water without an overall yield penalty in defined contexts. These are not contradictory when denominators and intervention definitions are made explicit.

The second conclusion is that plant-health management is hierarchical. Resistance, clean seed, rotation, residue management, balanced nitrogen, scouting, and forecasting should precede or determine fungicide decisions. FHB requires attention to DON and grain testing, not symptoms alone. Rust management requires surveillance because virulence changes. Seed treatments are useful but not universal. Biological control and digital diagnosis are promising complements that require local validation.

The third conclusion is that irrigation and disease outcomes are non-monotonic. Adequate water can sustain a healthier crop, yet excess water and nitrogen can produce dense, humid canopies; overhead wetting can prolong leaf wetness; and waterlogging can impose severe root-zone stress. Disease response is pathogen- and environment-specific. Water should not be withheld as a disease-control tactic because drought itself damages yield and plant health.

The fourth conclusion is that sustainability requires full accounting. Yield and WUE must be accompanied by water withdrawal, ET or consumptive use, soil salinity, drainage, groundwater, nutrient movement, pumping energy, GHGs, soil health, grain quality, profitability, and equity. Conservation agriculture can buffer warming and improve soil health in some settings, but it is not a universal package without residue, weed, rotation, machinery, and nutrient planning.

The fifth conclusion is that digital agriculture is decision infrastructure, not automatic impact. Soil sensors and weather models have the strongest wheat-specific evidence when connected to actions. UAV, satellite, AI/ML, climate-suitability, and VRI evidence remains partly predictive, transferable, or non-wheat-specific. Validation should show whether the technology improves decisions and outcomes across sites, seasons, cultivars, and farm types.

For Pakistan, the key conclusion is locally differentiated implementation. Waterlogging, salinity, groundwater dependence, disease hotspots, official-statistics definitions, smallholder finance, service markets, and extension all shape what is feasible. Modeled irrigation optima and surveillance percentages should not be presented as national causal prescriptions. A serviceable bundle—soil-water and groundwater monitoring, drainage and salinity management, stage-aware irrigation, resistant clean seed, disease surveillance, balanced nitrogen, and affordable advisory and repair services—is more defensible than a technology-only strategy.

Recommendations

Recommendation 1: Adopt a diagnose–plan–act–evaluate cycle

Extension and farm-management protocols should require a pre-irrigation checklist: soil water at representative depths, rainfall and forecast, crop stage, drainage and ponding, canopy density, nitrogen status, disease symptoms, cultivar resistance, and expected leaf-wetness risk. The decision should be documented as irrigate, delay, drain, scout, or treat, with the reason and subsequent outcome.

Recommendation 2: Protect critical stages but avoid universal prescriptions

Under limited supply, prioritize jointing/stem elongation, then consider anthesis and early grain filling according to local yield potential, soil water, rainfall, and disease risk. Moderate deficits should be tested against yield, WP, grain quality, and gross margin. Severe deficit should be treated as a risk boundary for research or emergency allocation, not as a default water-saving target.

Recommendation 3: Integrate water and nitrogen

N rates and timing should reflect soil mineral N, expected water supply, yield target, cultivar, canopy density, and disease risk. Avoid excess N where irrigation or rainfall will create a dense humid canopy. Evaluate protein and quality rather than infer them from yield. Do not assume that nitrogen increases or decreases disease uniformly across pathogens.

Recommendation 4: Make resistance and clean seed the foundation of IPM

Promote locally adapted, disease-resistant or less-susceptible cultivars, certified seed, uniform seed treatment, rotation, residue and volunteer management, and regionally relevant surveillance. Maintain resistance diversity and rapid communication when rust virulence changes. Use fungicides at registered rates and timings, rotate modes of action according to local stewardship guidance, and avoid routine calendar spraying when risk is low.

Recommendation 5: Treat FHB as a grain-health risk

At anthesis, combine weather and crop-stage forecasts with residue history, cultivar resistance, and scouting. Avoid nonessential canopy wetting during warm, rainy risk periods. If a registered fungicide is justified, apply it within the locally effective window with appropriate head coverage. Test grain for DON where risk and market requirements warrant; do not infer toxin safety from visible symptom suppression.

Recommendation 6: Build affordable digital services rather than isolated devices

Use low-cost soil sensors, weather data, and advisory channels with local calibration, multiple depths, representative stations, and fallback procedures. Combine satellite screening with UAV or ground confirmation where resources allow. Require external site/season validation for AI/ML. Digital advisories should explain uncertainty and include a human agronomic decision, not trigger automatic fungicide or irrigation without context.

Recommendation 7: Put drainage management and salinity diagnosis central

Before increasing irrigation, test irrigation and groundwater electrical conductivity, inspect drainage, and measure root-zone salinity where feasible. Water-saving recommendations should not encourage concentration of salts through inadequate leaching. Drainage, water-table monitoring, field leveling, and crop-specific tolerance testing should be included in Pakistan pilots.

Recommendation 8: Evaluate sustainability with a full dashboard

Every demonstration should record grain yield and stability; irrigation withdrawal; rainfall; soil-water change; ET or consumptive-use estimate; WP denominator; N uptake and N-use efficiency; soil EC and water table where relevant; pumping head and energy; fertilizer, pesticide, and labor costs; GHG indicators; grain protein, test weight, baking traits, and DON where relevant. This dashboard prevents a high ratio or high yield from masking environmental or quality costs.

Recommendation 9: Build Pakistan evidence through multi-location causal trials

A practical research design should compare farmer practice with ET/soil-water-balance scheduling, calibrated threshold sensing, locally relevant furrow or pressurized methods, jointing-focused and optional anthesis irrigation, balanced nitrogen, resistant versus locally common cultivars, certified seed and IPM, and contrasting drainage/salinity conditions. Trials should span arid and semi-arid sites, multiple seasons, and smallholder and larger farms. Disease endpoints should include rust, STB, mildew, FHB, and DON where epidemiologically relevant. The study should measure adoption, labor, repair, credit, gendered access, profitability, groundwater, energy, and equity, not only yield.

Recommendation 10: Deliver bundles through institutions and services

Technology adoption should be supported by extension, farmer field schools, local weather and disease advisories, custom-hire providers, repair networks, credit, certified-seed systems, and transparent water governance. Low-bandwidth SMS or voice advisories may be more scalable than app-only systems where connectivity is unreliable. Service providers should be trained to calibrate sensors, interpret forecasts, maintain pumps and filters, and follow fungicide stewardship. Efficiency should be monitored for rebound: if saved water expands irrigated area or pumping, basin-level withdrawals may not decline.

Table 8. Recommendations and implementation indicators

Recommendation	Immediate implementation action	Indicator delivery	of	Outcome indicator	Caution
Diagnose water and plant health together	Pre-irrigation checklist and field record	Share of irrigations with soil, stage, drainage, and disease observations	Fewer	saturated events; improved yield stability	Checklist quality must be audited
Protect critical stages	Jointing-first and conditional anthesis scheduling	Fields using calibrated thresholds or ET balance	Yield per irrigation and grain quality	No universal stage volume	
Integrate nitrogen and water	Soil-N and canopy-based N plan	N timing/rate recorded with irrigation	N-use efficiency, protein, disease risk	Pathogen-specific N response varies	
Foundation IPM	Resistant seed, certification, rotation, scouting	Certified-seed use, scouting frequency, resistance map	Disease progress, fungicide intensity, yield loss	Resistance can erode	
FHB/DON protection	Anthesis forecast, targeted spray, grain testing	At-risk fields receiving timely advisory	DON compliance and test weight	Symptom suppression is not toxin elimination	
Digital service	Calibrated sensors, weather and disease alerts	Sensor uptime, alert delivery, action logs	Water saved without yield/quality penalty	Requires fallback and local validation	

Drainage and salinity	EC, water table, ponding and drainage assessment	Fields with baseline EC/drainage record	Lower waterlogging and salinity stress	Leaching requires drainage
Full sustainability dashboard	Measure water, energy, soil, GHG, quality, profit	Complete seasonal dataset	Net margin and resource intensity	Boundaries must be explicit
Causal research	Pakistan Multi-location, multi-season factorial or staged trial	Sites, seasons, and farmer types represented	External validity and causal estimates	Avoid overloading trials without core outcomes
Inclusive scaling	Credit, custom hire, extension, repair, social learning	Smallholder and gender-disaggregated access	Sustained adoption and equity	Adoption association is not impact proof

Source: Author's synthesis of the reviewed evidence and implementation logic.

Final answer to the objectives and research questions

The six objectives are answered as follows. Objective 1 is answered by the ET–soil-water-balance–crop-stage framework. Objective 2 is answered by the conditional evidence for moderate deficit, supplemental, drip, micro-sprinkler, and well-managed furrow systems, with explicit denominator and transfer cautions. Objective 3 is answered by the resistance-first IPM hierarchy and disease-specific FHB, rust, STB, mildew, and seed-health measures. Objective 4 is answered by the non-monotonic interaction among water status, canopy humidity, nitrogen, waterlogging, salinity, and pathogens. Objective 5 is answered by the observations–inference–action digital architecture, with strongest evidence for sensor scheduling and weather forecasting and weaker evidence for generalized AI, UAV, and wheat VRI impacts. Objective 6 is answered by the Pakistan-specific service bundle, official-statistics reconciliation, differentiated surveillance, and causal research agenda.

Research Question 1 is answered: use a calibrated water balance and representative root-zone sensing, interpreted by stage, rainfall, soil, drainage, and forecast. Research Question 2 is answered: moderate and optimized water saving may improve WP, but severe or poorly timed deficit can reduce yield and quality; local validation is mandatory. Research Question 3 is answered: resistance, clean seed, cultural practices, scouting, forecasting, and targeted fungicides provide the most defensible hierarchy. Research Question 4 is answered: irrigation can protect crop vigor or intensify disease-favorable canopy conditions depending on water amount, method, timing, nitrogen, cultivar, and weather. Research Question 5 is answered: digital tools are credible when validated across sites and linked to action; predictive accuracy alone is insufficient. Research Question 6 is answered: Pakistan needs locally calibrated, affordable, governed bundles that address water quality, drainage, disease hotspots, energy, extension, credit, and service access.

Closing perspective

The central contribution of this review is a disciplined shift from “more irrigation” or “more technology” toward synchronized decisions. Diagnose the soil, crop, weather, disease, and service context; plan around a stated objective; protect sensitive stages; keep canopies and root zones healthy; evaluate water, grain, energy, and equity together; and feed the evidence back into the next season. Such integration is more cautious than a universal recipe, but it is more scientifically defensible and more likely to remain useful under climate uncertainty.

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