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CLIMATE-RESILIENT WHEAT CULTIVATION IN ARID SIBI, BALOCHISTAN

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Abstract

This study investigates the impact of climate variability on wheat cultivation in the arid region of Sibi, Balochistan, where agriculture is highly exposed to water scarcity and erratic rainfall. With nearly 40% of farmland under wheat, the objective was to identify the most suitable variety for sustainable production under limited water availability. FAO's CROPWAT model was applied to estimate crop water requirements (CWR), irrigation scheduling, and yield response to water stress (Ky) for four varieties: Dilkash-20, Lalma, Wafaq-23, and Arooj. Climatic, soil, and crop data from 2024 were used to calculate evapotranspiration, effective rainfall, and irrigation demand. Results indicate that Lalma demonstrated the greatest drought tolerance (Ky = 0.41), making it most suitable for water-scarce conditions, while Dilkash-20 and Arooj exhibited high sensitivity (Ky > 2.5). Although rainfall in 2024 reduced irrigation demand, projections suggest increasing water requirements under rising temperatures and declining precipitation. The study recommends adoption of smart irrigation, drought-tolerant varieties, conservation agriculture, and supportive water management policies to ensure sustainable wheat production in arid environments.

INTRODUCTION

Pakistan, located in South Asia (30.37°N, 69.34°E), spans 881,913 km² and features diverse topography ranging from the Himalayan and Karakoram ranges in the north to arid plains and deserts in the south [1]. The country has a predominantly arid to semi-arid climate, characterized by hot summers, mild winters, and highly variable monsoon-driven rainfall, ranging from <100 mm in deserts to >1500 mm in the northern highlands [2]. Agriculture, a cornerstone of the economy, employs 38% of the workforce and contributes 19% to GDP [3]. Sustained by the Indus Basin Irrigation System (IBIS)—one of the world's largest contiguous irrigation networks—the sector is increasingly constrained by land degradation, population growth, water scarcity, and climate change [4-5].

Pakistan is now classified as water-scarce, with per capita availability declining from 5,000 m³ in 1951 to <1,000 m³ in 2020 [6]. The Indus River and its tributaries provide ˜80% of surface water, but inefficiencies in IBIS, groundwater depletion, and climate-induced glacial melt and altered rainfall patterns exacerbate stress [5, 7]. These factors threaten agricultural productivity, food security, and rural livelihoods.

Major crops—wheat, rice, cotton, sugarcane, and maize—dominate agricultural production, with wheat as the staple Rabi crop and rice as a major Kharif crop and export commodity [3]. Together, these crops occupy most irrigated land, with ~90% supported by the IBIS [8].

Balochistan, the largest province by area (28.49°N, 65.09°E), contributes <4% of Pakistan's cultivated land but dominates fruit production, supplying >90% of apples, grapes, almonds, pomegranates, and dates [1]. Field crops include wheat, barley, maize, canola, gram, and fodder, largely supported by groundwater extraction through tube wells and traditional karezes [9]. In Sibi district, with a hot semi-arid climate and limited rainfall, wheat is a major Rabi crop, alongside cotton, pulses, and vegetables. Livestock, especially the renowned Bhagnari cattle, also supports the local economy [10]. However, water scarcity, high evapotranspiration, and limited arable land constrain agricultural productivity [11].

Sibi's hot arid climate and unpredictable rainfall pose critical challenges for wheat cultivation, which covers ~40% of the cultivated area. Limited research exists to identify wheat varieties suited for sustainable production under these conditions.

The objective was to identify the most suitable wheat variety for sustainable production in Sibi under limited water availability and arid climatic conditions, thereby enhancing climate resilience in wheat cultivation.

The study contributes to climate-resilient agriculture in water-scarce regions by applying the FAO CROPWAT model to assess crop water requirements, irrigation scheduling, and yield response. Findings will support farmers, policymakers, and planners in making informed decisions on variety selection, irrigation management, and resource allocation, ultimately strengthening food security and sustainable agriculture in Sibi, Balochistan.

Materials and Methods

The study was conducted in Sibi, Balochistan shown in figure 1, characterized by extremely hot summers (up to 52°C), mild winters, and low, irregular rainfall. Agriculture is the primary livelihood, with wheat occupying ~40% of cultivated land, followed by cotton (25%), rice (15%), maize (10%), and barley/others (10%) [12].

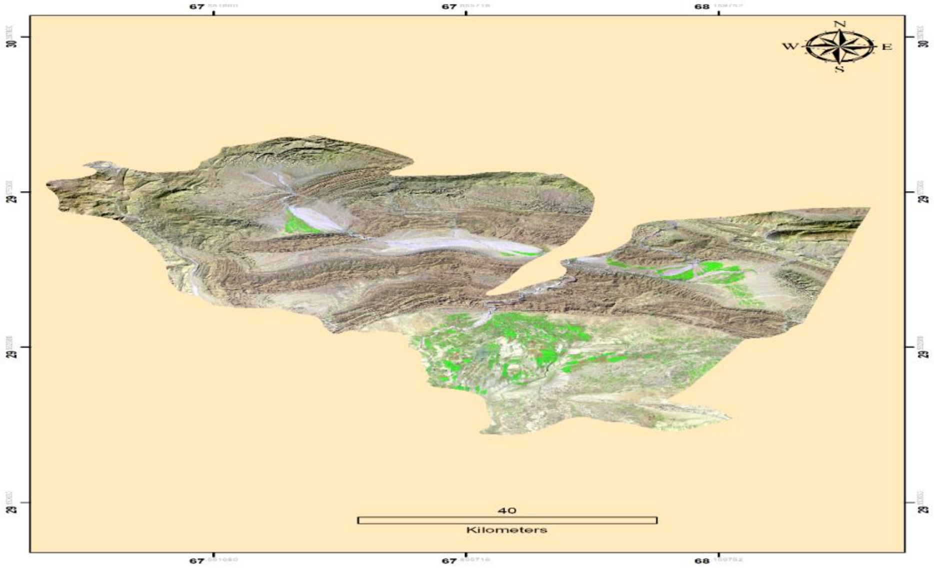

Figure 1. Map of Study Area

Climate data for 2024 were obtained from the Pakistan Meteorological Department, including minimum and maximum temperature, wind speed, relative humidity, sunshine hours, and rainfall. Reference evapotranspiration (ETo) was calculated using the FAO Penman-Monteith method on a daily and monthly basis.

Rainfall and effective rainfall were derived from 2024 meteorological records and computed in CROPWAT 8.0. Effective rainfall was used to estimate water availability for wheat at different growth stages and its impact on yield and irrigation demand.

Crop parameters included growth stage duration, crop coefficients (Kc), rooting depth, critical depletion, and yield response factor (Ky). The Ky value was calculated using FAO methodology to assess yield sensitivity to water stress [4]. Four wheat varieties—Dilkash-20, Lalma, Wafaq-23, and Arooj—were evaluated.

Soil input data for CROPWAT included total available water content, maximum infiltration rate, rooting depth, and initial soil moisture conditions. These parameters were used to simulate water balance during the wheat growth cycle.

FAO's CROPWAT 8.0 model was employed to estimate crop water requirements (CWR), evapotranspiration (ETc), effective rainfall, and irrigation demand across different growth stages.

CROPWAT was further used to develop irrigation schedules, providing net and gross irrigation requirements, flow rates (L/s/ha), and daily soil moisture balance. Figure 2 showing Conceptual framework of the study showing the use of climatic, soil, and crop parameters in the CROPWAT model to evaluate water requirements, irrigation scheduling, and drought tolerance of wheat varieties in Sibbi, Balochistan.

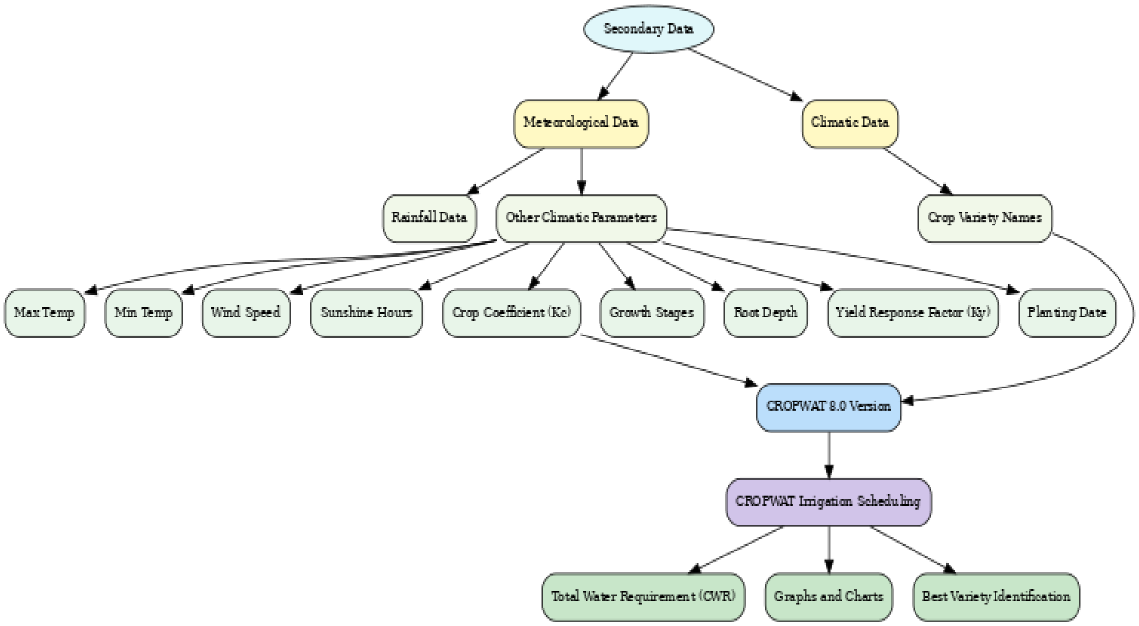

Figure 2. Conceptual Farmwork

Results and Discussions

Climatic Conditions: Meteorological data from MO Sibbi-4 station indicated extreme seasonal variability in temperature and atmospheric water demand. The highest mean maximum temperature occurred in June (45.9 °C), while the lowest mean minimum temperature was recorded in January (6.8 °C). Reference evapotranspiration (ETo), calculated using the FAO Penman–Monteith method, averaged 3.13 mm day^{-1} annually, with a peak of 5.14 mm day^{-1} in July and a minimum of 1.14 mm day^{-1} in January. These pronounced fluctuations highlight the strong seasonal variation in evaporative demand, which directly governs crop evapotranspiration and irrigation scheduling requirements (figure 3).

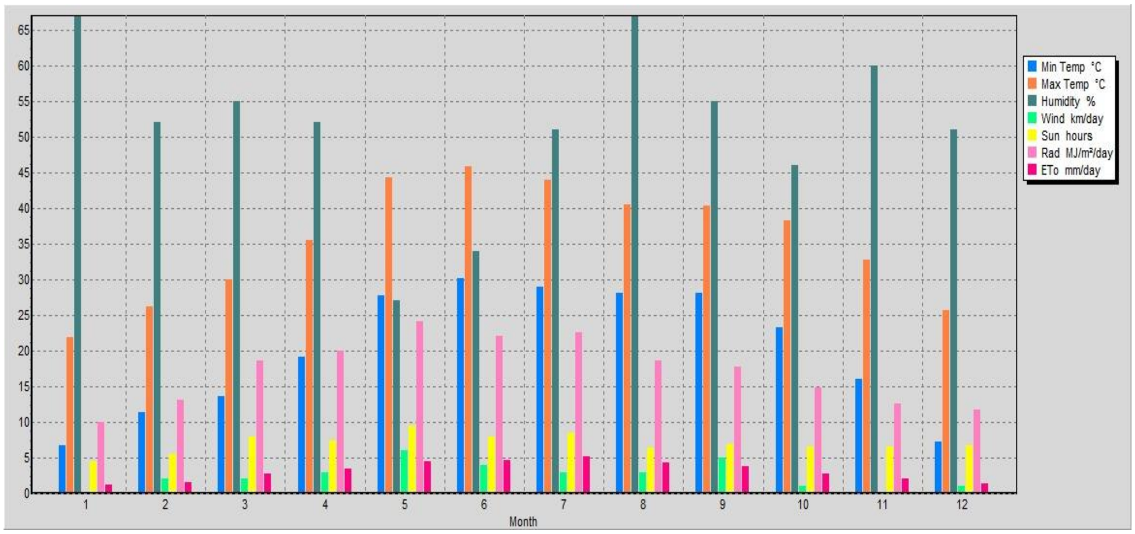

Figure 3: Monthly Reference Evapotranspiration (ETo) and Climatic Parameters in Sibi District (2024)

Rainfall and Effective Rainfall: Total annual rainfall for 2024 was 425 mm, of which 347.4 mm was classified as effective based on the USDA-SCS method incorporated in CROPWAT 8.0. Rainfall was highly concentrated during the monsoon, with maxima recorded in July (167 mm) and August (115 mm). This distribution contributed substantially to effective water availability during the late wheat growth stages. Climatic inputs, combined with soil and crop parameters, were used to model crop evapotranspiration (ETc), crop water requirements (CWR), and yield response to water stress (Ky) for four wheat varieties—Dilkash-20, Lalma, Wafaq-23, and Arooj—under uniform sowing (3 December) and harvesting (11 April) dates (figure 4). Growth stages were defined as 20 days (initial), 30 days (development), 50 days (mid-season), and 30 days (late-season), with red loamy soils as the baseline.

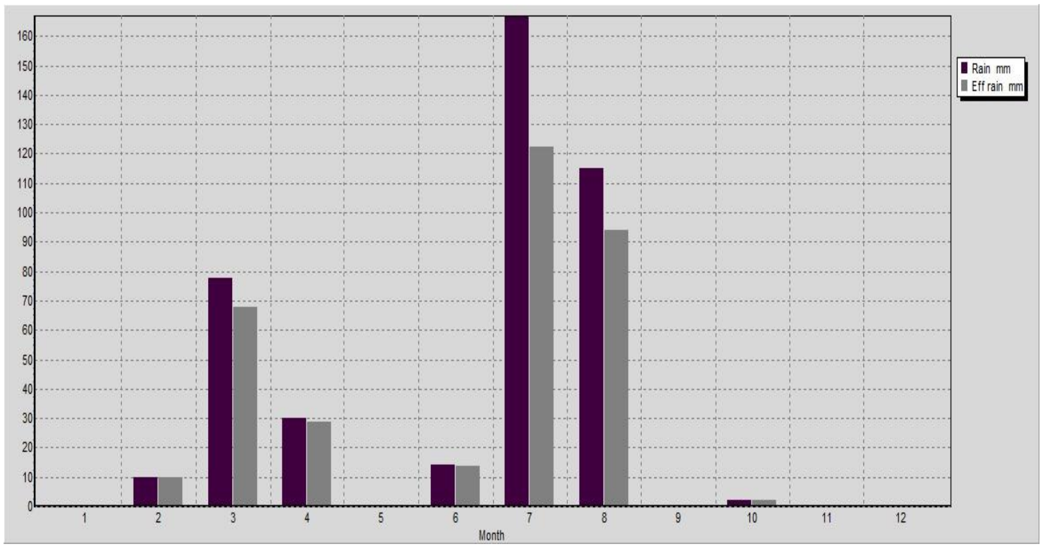

Figure 4. The graph between rainfall and effective rainfall

3.3. Crop Water Requirement and Yield Response: Dilkash-20 exhibited the highest sensitivity to water stress, with yields projected to decline sharply under deficit irrigation conditions. Lalma demonstrated strong drought tolerance, showing minimal yield reduction under limited water supply, making it the most suitable for semi-arid conditions. Wafaq-23 displayed moderate sensitivity, offering a balance between drought resilience and productivity. Arooj, like Dilkash-20, was highly vulnerable to water stress, making its performance heavily reliant on assured irrigation (Table 1).

Table 1: Comparative Results of Wheat Varieties under Water Stress

Variety	**ETc (mm)**	**Eff. Rainfall (mm)**	**Net Irrigation Req. (mm)**	**Actual Irrigation (mm)**	**Ky**	**Drought Sensitivity**
Dilkash-20	197.2	101.6	96.5	84.1	3.13	Highly Sensitive
Lalma	196.4	101.6	95.7	84.1	0.41	Strongly tolerant
Wafaq-23	197.2	101.6	96.5	84.1	1	Moderately Sensitive
Arooj	197.2	101.6	96.5	84.1	2.55	Highly Sensitive

ETc= Crop evapotranspiration; Ky= Yield Response Factor. Value stimulated using FAO CROPWAT 8.0 under uniform climatic and soil condition in Sibbi, Balochistan

Although the 2024 season received sufficient rainfall to avoid yield penalties, Ky values revealed significant inter-varietal differences in drought response. Lalma was identified as the most water-efficient and drought-resilient, while Dilkash-20 and Arooj were the most stress-prone.

3.4. Irrigation Scheduling and Efficiency: Irrigation scheduling simulations indicated peak crop water demand during the mid-season stage (February–March), coinciding with maximum ETc value (figure 5). Although rainfall distribution during this period largely met crop water needs, supplemental irrigation was necessary to buffer potential shortfalls. Due to uniform planting dates and soil conditions, irrigation schedules remained consistent across varieties; however, varietal performance under water stress was differentiated by Ky values. Agricultural water management in arid zones like Sibi hinges on understanding climatic drivers of crop water demand. The following sections analyze key hydrological variables, evapotranspiration, rainfall, and temperature trends, to quantify current and future irrigation challenges for wheat systems.

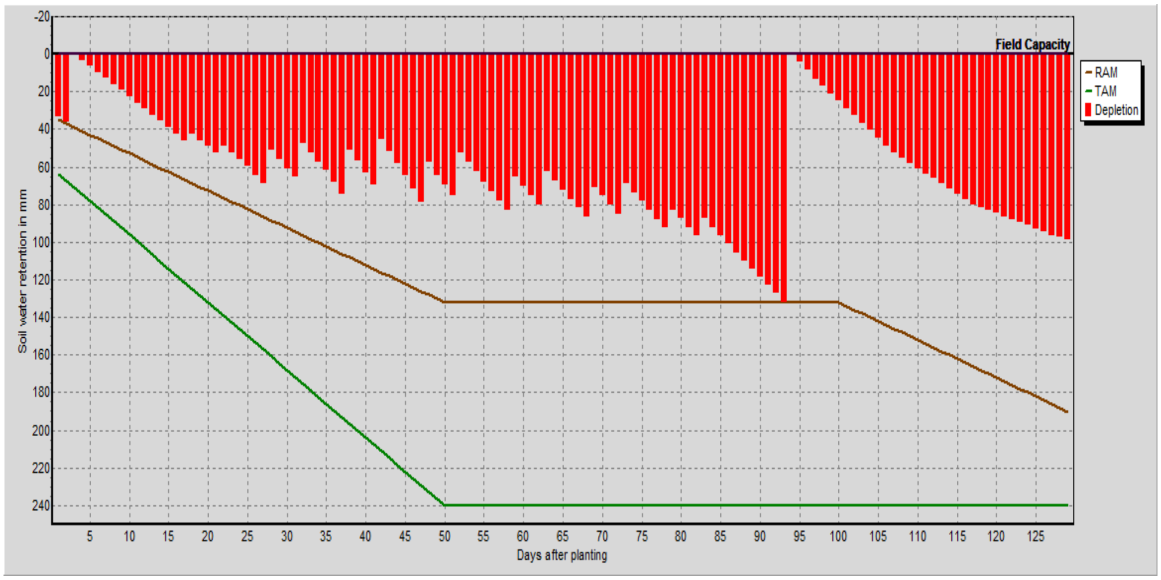

Figure 5. Irrigation Scheduling Curve – Wheat Growth Stages vs ETc & Effective Rainfall

3.5. Climatic Drivers of Evapotranspiration and Water Demand: The figure 2 shows that (ETo) values in Sibi are strongly unimodal with values peaking in July (5.14 mm/day) and greater than 4 mm/day from May through August, as shown by the output of CROPWAT. This is in line with FAO's Penman–Monteith guidelines of high solar radiation, low relative humidity and hot temperature being important ETo forcing factors in arid regions [13]. Mean maximum temperature in the peak summer months (44.3 °C in May and 45.9 °C in June) and daily sunshine of more than 9 hours (May–July) when coupled with each other increase atmospheric evaporative demand (figure 2). In Pakistan, analogous ETo behaviour values above 5 (mm/day) during June–July are reported for similar semi-arid regions, like Peshawar, with similar solar radiation and wind speeds [14]. During the critical wheat mid-season (February–March) ETo is elevated and, if not offset by irrigation or rainfall, crop water stress could start as early as late February with crop (ETc) of 2.23 mm/day (mid stage) and 1.12 mm/day (mid stage) [15]. This necessitates pre-emptive irrigation scheduling in February to offset atmospheric demand before stress onset.

3.6. Rainfall Patterns and Effective Precipitation: Sibi receives only 425 mm of annual rainfall, of which 282 mm (67%) falls in July–August. Effective rainfall is then further decreased to 347.4 mm (with runoff and deep percolation losses by applying the USDA SCS Effective rainfall formula, which discounts total rainfall for runoff and deep percolation losses based on soil type and rainfall intensity. For farmers, this means only ~82% of observed rainfall (347.4 mm vs. 425 mm) is actually plant-available, requiring them to supplement irrigation beyond apparent rainfall totals. Wheat mid-season partly coincides with monsoonal rains (March–April) and the rest of effective precipitation must be assigned carefully to meet ETc. Balochistan rainfall analyses reveal decreasing rainfall on a long-term basis averaging approximately 2.9 mm/year which implies an additional decrease in rainfall for Sibi. The inherently erratic rainfall regime of Sibi therefore further enhances dependence on supplemental irrigation, since only ~52% of seasonal ETc (101.6 mm out of ~197 mm) is met by effective precipitation under current climate.

3.7. Crop Water Requirements and Deficit Analysis: Even though Dilkash-20, Lalma, Wafaq-23 and Arooj have different yield response factors and phonologies, seasonal ETc and irrigation requirements differ by less than 0.00027mm/day between cultivars (Tables 1). For example, 197.2 mm of crop water (ETc) is needed by Dilkash-20 and Wafaq-23 in a season, of which 101.6 mm is supplied by effective rainfall and the net deficit is ~96 mm (Table 1). According to literature in semi-arid wheat systems in Pakistan, total seasonal ETc for irrigated wheat are reported to be between 180–220 mm and similar effective rainfall contributions result in similar demand for irrigation [16]. Given an ideal irrigation schedule (100% refilling at 100% soil moisture depletion), yields can therefore be simulated to zero-percent reduction across all cultivars suggesting that it is possible to avoid water stress. Field realities, though, result in an uneven distribution of irrigation water, poor field-application efficiency (70% assumed here; Field efficiency can be raised to 85% via laser land levelling, drip systems, and lined canals, reducing losses by 15%.) and fluctuating groundwater availability and, therefore, meeting this ~96 mm deficit is difficult during years of below-average rainfall. To enhance the irrigation water efficiency above 70% farmer can adopt sustainable practice such as mulching, intercropping, raveling system, drip irrigation, pitcher irrigation system and other different techniques that improve soil health and increase water efficiency by 83-90% and also control the water loses.

3.8. Trends in Temperature and Rainfall: Longitudinal studies in Balochistan indicate warming trend of 0.029 °C/year (1980–2017) and accompanying annual precipitation reduction of 2.896 mm/year (Zhob district proxy for Sibi) [17]. Between 1980 and 2021, regionally, mean annual temperatures have increased ~0.9 °C and both wheat phenology and ETo have been directly affected. Future rabi season (Oct–Apr) precipitation projections for Pakistan by 2050, under RCP and SSP scenarios, show further precipitation declines of 0.0011mm/day - 0.0044mm/day along with mean temperature rises of 1 – 2 °C [13]. At higher temperatures, peak ETo is probably increased during April–June which will shift crop-water demand curves to the left and intensify mid-season deficits. The fraction of rain meeting crop needs, however, will shrink as ETc rises, even if effective rainfall is unchanged in absolute terms. As a result, the seasonal irrigation requirement could increase from ~96 mm to potentially 110–120 mm by mid-century, assuming no adaptation [14,17].

3.9. Impact on Wheat Production and Yield Projections: Results of several empirical studies in Pakistan reveal that rice and wheat yields decline by 4–5% and 2–4% respectively under irrigated conditions and by 3–5% and 3% respectively under rainfed conditions associated with 1°C increase in the mean temperature during the rice and wheat growing seasons, as a result of heat stress during anthesis and reduced duration of grain filling [18]. Warmer temperatures accelerate phenology, shortening the grain-filling stage by 5–7 days per 1°C rise, reducing yield potential by 3–5% even with irrigation. Sibi's late-rabi wheat is also exposed to peak temperatures well above 30 °C during March (max 30 °C; min 13.6 °C) Timing irrigation to pre-dawn hours during flowering (anthesis) can lower canopy temperatures by 2–3°C, mitigating heat damage, so heat induced yield reductions may be expected even with irrigation. Also, monsoonal rainfall can be shifted later into late-sowing windows, requiring the adjustment of planting dates into hotter times of the year [13]. A zero-yield-reduction simulation given perfect irrigation is shown today, but literature warns that higher pest and disease pressures like rust diseases, powdery mildew, and Fusarium Head Blight , with warmer, more humid monsoons can further reduce yield by a further 5–10%: Warmer winters amplify rust fungus and aphid infestations, requiring integrated pest management to prevent additional losses, depending on their response to integrated pest management [19].

3.10. Adaptation Strategies:

Traditional flood irrigation and fixed-schedule watering are inadequate for future stresses.

Transition to climate-smart practices is critical. To mitigate rising water demand and heat stress:

Drought- and Heat-Tolerant Cultivars (low-cost, immediate): Wheat breeding programs in Balochistan are initiated to develop wheat lines having deeper root system and higher leaf area index to maximize water uptake and keep cooler canopy [20]. Also, the cultivars Lalma and Arooj show lower Kc values during the mid-season (1.11–1.12) than other varieties (Table 1) which can reduce the seasonal ETc by ~1–2 mm. This water saving is marginal but could mean 1–2% yield improvements under water-scarce conditions [16]

Deficit Irrigation and Scheduling (moderate cost, high impact):

PRD is a water-saving irrigation technique. PRD applied during initial plant growth (Kc≈0.30–0.41) and late maturation (Kc≈0.35–0.49), can save as much as 10 to 15 mm of water per growth season without yield penalty [21]. Applying this to Sibi's ~96 mm deficit, this would imply potential savings of 10–15% of total irrigation water. Irrigation can be realigned to coincide with monsoonal pulses (July–August), instead of fixed decades where irrigation can better utilize effective rainfall and limit deep percolation losses [13, 16].

Conservation Agriculture and Soil Moisture Retention (technical training needed):

Practices like no-till and permanent raised beds retain residual soil moisture, reducing evaporation by ~10–20 mm per season and improving infiltration during infrequent rain events [17]. In Sibi's red-loamy soils (FC–WP = 180 mm/m), if adopted, this could increase available water by ~5–10% during critical growth stages. Mulching with crop residues or plastic sheets from November to February can lower soil temperature by 1–2 °C and evaporation by 15–20% [20, 22].

Alternate Cropping and Agronomic Restructuring (long-term investment):

Based on Balochistan's promotion of low water crops such as olives and pistachio, a part of marginal wheat area can be converted to drought tolerant horticultural species which will reduce sum water demand and generate income diversification [12, 23].

Intercropping wheat with legumes (e.g., chickpea) in February–April can enhance soil structure and enhance 10–15% of water-use efficiency. In Zhob, wheat-chickpea intercropping increased net income by 22% while reducing water use by 15% [17].

3.11. Policy and Institutional Implications:

The Balochistan government attempts to penalise groundwater over-extraction and promote equitable water distribution are efforts to tackle supply-side constraints. Community-led water user associations can democratize allocation, maintain infrastructure, and promote rainwater harvesting at village scales. Volumetric allocations based on cadastral mapping can guarantee sustainability of meeting of Sibi's ~96 mm seasonal irrigation demand per hectare [12, 20]. Groundwater policies should mandate water-efficient technologies (e.g., subsidized drip kits) and enforce extraction limits using smart metering.

Localized irrigation scheduling (e.g. scheduling irrigation based on forecasts for end-of-month effective rainfall at the farm level) must also be relayed in extension programs and conservation agriculture must be promoted. Farmers can receive real-time weather advisories, using remote-sensing data and mobile SMS platform to determine optimal sowing windows and irrigation timing, possibly reducing up to 10.

This study examined how different wheat varieties perform under water-scarce conditions in Sibi, Balochistan, a region with extreme heat and very low rainfall. Using the CROPWAT model, the study calculated the water needs of four wheat varieties: Dilkash-20, Lalma, Wafaq-23, and Arooj. The results showed that Lalma is the most drought-tolerant variety, with a low response to water stress. On the other hand, Dilkash-20 and Arooj are more sensitive and may not perform well without extra irrigation. Even though rainfall in 2024 was enough to meet most crop needs, the study found that additional irrigation is still necessary during the key growth stages, especially in February and March. These findings show the importance of selecting the right wheat variety and planning irrigation carefully to avoid yield losses. As water scarcity and climate change continue to affect farming in Balochistan, it is important to promote water-efficient crops. Improve irrigation practices and support farmers with better planning tools. Models like CROPWAT can help farmers, researchers, and policymakers make better decisions about crop selection and water use. This study can be useful not only for Sibi but also for other dry areas around the world that face similar farming challenges 12% yield loss [13, 19]. It is estimated that the additional locally available water from construction of small check dams and rainwater harvesting structures in upstream catchments would be as much as 20 mm/year, bridging a fifth of the seasonal deficit. On-farm water storage has been valuable in Balochistan's pilot projects for pistachios [23] and scaling up pistachios should go along with scaling up pistachios in wheat belt areas [15]. In Pakistan the different polices and strategies where interpreted, which also work successfully like IWRM, BGRMA and NSDS and many more. The BGRMA 2019 successfully works in Balochistan. The BGRMA 2019, which is used to regulate the groundwater (management) certification, water right allocation and encouraging water efficient practices. Like bottle irrigation. It also meets with IWRM to support community and fair distribution of water.

Moreover, the Pakistan National Adaptation Plan highlights the climatic-resilient agriculture, rainwater management, and smart agriculture practices. In summary, Sibi's high ETo (>4 mm/day in summer), erratic rainfall, and crop-specific water sensitivities necessitate precision irrigation. Lalma's drought tolerance offers resilience, but future climate projections demand urgent adaptation in water management.

Conclusion

This study assessed the water requirements and drought response of four wheat varieties in the arid climate of Sibi, Balochistan, using the FAO CROPWAT model. Results demonstrated clear varietal differences in water-use efficiency and yield sensitivity to water stress. Lalma emerged as the most drought-tolerant (Ky = 0.41), making it highly suitable for water-scarce environments, while Dilkash-20 and Arooj (Ky > 2.5) were highly stress-sensitive and dependent on reliable irrigation. Wafaq-23 exhibited intermediate performance, balancing resilience, and productivity. Despite sufficient rainfall during 2024, simulations highlighted the necessity of supplemental irrigation during critical growth stages (February–March) to prevent moisture deficits. These findings underscore the importance of variety selection, optimized irrigation scheduling, and climate-smart management practices for sustaining wheat production under increasing water scarcity. By integrating models such as CROPWAT into agricultural planning, policymakers, researchers, and farmers can improve water resource management, strengthen food security, and enhance climate resilience not only in Sibi but also across other arid and semi-arid regions facing similar challenges.

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