Utilize the irriWatch portal and Spectral Fingerprinting in precision agriculture to assess soil moisture, evapotranspiration, water efficiency, and biomass throughout various wheat growth stages.

Heman Abdulkhaleq A. Gaznayee
Department of Forestry, College of Agricultural Engineering Sciences, Salahaddin University-Erbil, Erbil, Kurdistan Region, Iraq; heman.ahmed@su.edu.krd;
ORCID : https://orcid.org/0000-0002-1549-407X

Abstract

Precision agriculture encompasses a suite of cutting-edge technologies that integrate sensors, advanced machinery, information systems, and strategic management to optimize production by addressing the variability and uncertainties inherent in agricultural systems. This study explores the seasonal fluctuations in vegetation cover, soil moisture, nitrogen uptake, carbon supply, water use, and dry matter production in a wheat-growing system using Satellite Remote Sensing Acquisition via the IrriWatch Portal. The evolution of vegetation cover progresses from minimal levels during the establishment phase to peak coverage (75–100%) in March-April, followed by a gradual decline towards harvest. This pattern mirrors the life cycle of the wheat crop, with peak vegetation indicating maximum photosynthesis and biomass production. During the initial establishment phase (December-February), nitrogen demand remained minimal, primarily supporting root growth. As the vegetative phase begins in February and extends through April, nitrogen uptake accelerates, with leaf nitrogen content peaking at 2.5–2.6%. Approximately 70–80% of the cumulative carbon supply is contributed by carbon inputs from roots and microbial activity. By harvest (May-June), the cumulative carbon supply reaches 2,200 mg/kg, stabilizing soil organic matter at 1,650 mg/kg.Water utilization trends demonstrate a balance between natural precipitation and irrigation. Precipitation meets 20–30% of seasonal water requirements, while irrigation supplies 70–80%, particularly during the vegetative and reproductive stages. Evapotranspiration (ETa) peaks at 6–7 mm/day during March-April, driven by transpiration from the crop canopy. Under ideal conditions, wheat crops achieve a biomass yield of 28,000 kg/ha. However, actual field conditions often result in yields stabilizing around 22,000 kg/ha. The vegetative phase (February-April) accounts for 70–80% of total biomass accumulation. In conclusion, effective resource management—through precise irrigation, optimized nitrogen application, and carbon input—enhances wheat productivity and sustainability. Remote sensing tools like IrriWatch enable better decision-making, ensuring sustainable practices that improve yields while maintaining long-term soil health and resource efficiency.

Keywords: Wheat productivity, Soil moisture dynamics, Evapotranspiration (ETa), Water use efficiency, Precision agriculture and Crop growth stages

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Introduction

Precision agriculture has garnered significant attention within the agricultural sector over the past decade of the twentieth century. Wheat (Triticum aestivum) is among the most widely cultivated cereal crops on a global scale, functioning as a staple food source for a substantial segment of the global population. Given its essential importance in ensuring food security, enhancing wheat production is crucial, particularly in light of climate variability and escalating water scarcity [1]. Irrigation constitutes a vital agricultural practice that guarantees adequate water supply for wheat farming, especially in areas experiencing limited rainfall. Nonetheless, conventional irrigation techniques frequently lead to inefficiencies, such as over-irrigation or water stress, which negatively affect soil moisture, evapotranspiration, water use efficiency (WUE), and overall biomass production [2 .[

The emergence of remote sensing technologies has transformed precision agriculture, offering innovative resources for the real-time monitoring and management of crop irrigation practices. Remote sensing serves as a robust method for gathering spatial and temporal data on essential biophysical parameters, including soil moisture, evapotranspiration (ETa), WUE, and biomass accumulation [3]. Systems such as IrriWatch, which combines high-resolution satellite imagery with field-level models, have shown considerable promise in enhancing irrigation efficiency and optimizing resource distribution in wheat cultivation [4]. Soil moisture is a critical factor in assessing the availability of water for crops, exerting a direct influence on plant growth, evapotranspiration, and nutrient uptake [5]. The effective management of soil moisture throughout the various growth stages of wheat is vital for sustaining optimal plant health and maximizing yields. Remote sensing technologies provide dependable methods for monitoring soil moisture at different depths and across varying spatial scales. By integrating satellite imagery with Field data, these systems yield real-time insights into the dynamics of soil moisture, facilitating precise irrigation scheduling that aligns with the specific requirements of the crop at distinct growth stages [6 .[

The study employs IrriWatch to oversee wheat irrigation practices with the objective of optimizing these practices and enhancing productivity. The importance of sustaining soil water potential is underscored; as effective irrigation strategies mitigate the risk of water-logging. The significance of managing soil water potential is further emphasized for achieving optimal growth conditions. Maintaining soil water potential is essential for ensuring optimal growth and irrigation efficacy .

Precision agriculture aligns with the Sustainable Development Goals (SDGs) as it fosters the efficient use of resources, bolsters food security, and advocates for the adoption of sustainable agricultural methodologies. The application of advanced techniques such as remote sensing and the deployment of sophisticated tools like IrriWatch significantly contribute to the advancement of SDG 2 (Zero Hunger) by optimizing wheat production and further support the realization of SDG 6 (Clean Water and Sanitation) through enhanced irrigation efficiency and the promotion of water conservation practices.

Material and Methods

Study Area

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The research was conducted in Karbala, Iraq (32.607, 44.035), situated in the central-southern region of the country. Karbala is known for its arid climate, characterized by limited and irregular rainfall, necessitating the use of irrigation in agricultural practices [7]. The wheat fields in this area primarily employ center pivot systems for irrigation, renowned for their effectiveness in uniformly dispersing water throughout the fields. The climatic conditions, marked by high temperatures and low humidity, offer an optimal setting for assessing sophisticated irrigation management systems [8]. This study monitored the cultivation of wheat throughout a growing season spanning from December to July, covering all crucial growth stages: establishment, vegetative, reproductive, and grain-filling phases [9.[

Methodology

Data Collection: This study employed the IrriWatch system, a remote sensing-based technology that integrates high-resolution satellite imagery with ground-level data to effectively monitor and manage irrigation practices [10]. The primary parameters measured were:

Soil Moisture Dynamics: Soil moisture levels were monitored using a combination of ground-based sensors and satellite data, capturing spatial and temporal variations at multiple soil depths [11.[

Evapotranspiration Monitoring: ETa was estimated using satellite-derived surface energy balance models, providing daily insights into crop water loss [12.[

Growth Stage-Specific Analysis: Data were collected for four primary wheat growth stages:

A.Establishment Stage (December–January): Ensuring adequate soil moisture for germination and early root development [13.[

B.Vegetative Stage (January–March): Maintaining high soil moisture levels to support rapid canopy growth and photosynthesis [14.[

C.Reproductive Stage (April–May): Meeting peak water demands to support flowering and grain filling [15.[

D.Maturity Stage (May–July): Managing reduced water requirements during grain maturation and harvest [16.[

Data Analysis

The collected data were subjected to statistical and spatial analyses to establish relationships between irrigation practices and crop performance. Key aspects of the analysis included: The study demonstrated the effectiveness of integrating remote sensing technologies like IrriWatch in enhancing irrigation management practices, improving wheat productivity, and promoting sustainable agriculture in semi-arid regions.

Evapotranspiration Patterns: ETa trends were analyzed to identify periods of peak water demand and evaluate irrigation efficiency [17]. The estimation of evapotranspiration (ETa) was conducted utilizing the surface energy balance model:

$$ETa = Rn - G - H / \lambda$$

Where: Rn represents the net radiation at the surface (W/m²), G denotes the soil heat flux (W/m²), H indicates the sensible heat flux (W/m²), and λ symbolizes the latent heat of vaporization (J/kg(

Water Utilization Efficiency (WUE) Calculation:

WUE was calculated as the ratio of biomass produced to the total water consumed through irrigation and precipitation [18]. Water Use Efficiency (WUE) is determined as: $WUE = B/W$

Where: B signifies the biomass produced (kg/ha), and W represents the total water consumed (mm), encompassing irrigation and precipitation

Water Use Efficiency:

WUE was calculated to measure the productivity of water use relative to biomass production[18]. The effectiveness of irrigation scheduling can be evaluated using:

ISE = Ireq / Iapp

Where: Ireq indicates the irrigation water required by the crop (mm), and Iapp represents the actual irrigation water applied (mm(

Normalized Difference Vegetation Index (NDVI): Biomass production was estimated using vegetation indices, including the Normalized Difference Vegetation Index (NDVI), derived from satellite imagery [19]. NDVI, utilized for biomass accumulation, is computed as:

NDVI = (NIR - R) / (NIR + R(

Where: NIR stands for Near-Infrared reflectance, and R represents Red reflectance

Soil Moisture Availability (SMA(

Soil Moisture Trends: Variations in soil moisture levels were examined across growth stages to assess irrigation efficiency [18]. The assessment of soil moisture availability is based on the ratio of available water to the total available water capacity:

SMA= (θ - θwp)/ (θfc - θwp(

Where: θ denotes the current soil moisture content (m^3/m^3), θwp signifies the Wilting point (m^3/m^3), and θfc represents the Field capacity (m^3/m^3)

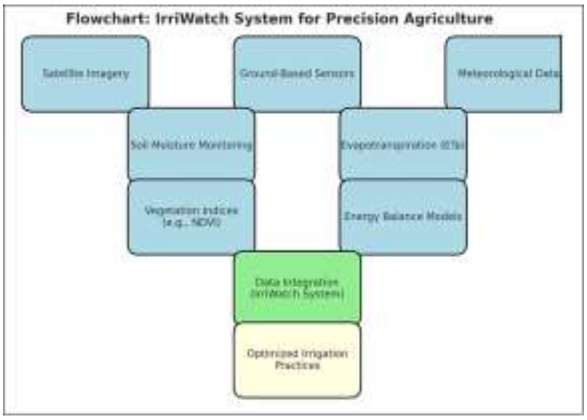

Figure 1. Flowchart on the "IrriWatch System: Workflow for Precision Agriculture and Optimized Irrigation Management.

Biomass Correlation: Biomass growth trends were correlated with irrigation and ETa data to evaluate the impact of water management on crop productivity [19]. The correlation between biomass production and evapotranspiration can be articulated as :

B = k·ETa

Where: B represents the biomass production (kg/ha), k signifies the crop-specific coefficient, and ETa stands for Evapotranspiration (mm).

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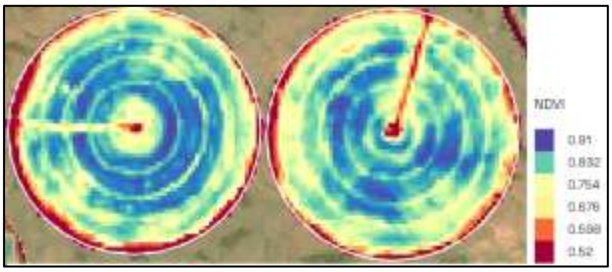

Figure 2. Displays the central pivots situated in the province of Karbala, highlighting the significance of monitoring the daily variations in NDVI across different stages of growth.

Results and Discussion

Vegetation Cover

The progression of vegetation covers from low to high and back to low reflects the life cycle of wheat, from germination to maturity and harvest. Monitoring vegetation cover percentages can help farmers optimize irrigation, fertilization, and pest management during key growth stages. The peak vegetation period (March-April) is particularly critical for determining yield potential, as it indicates maximum photosynthetic activity and biomass accumulation.

The Figure 3 illustrates the fluctuations in vegetation cover percentage for wheat in a center pivot located in Karbala province over the course of the growing season, commencing in December and culminating at harvest. The vegetation cover percentage signifies the extent of the ground surface enveloped by the crop's canopy. Here is a breakdown of the stages based on the percentage. During the Initial Stage (December to January), the vegetation cover is minimal, ranging from 0–10%. This period denotes the emergence of wheat seedlings, characterized by sparse growth, marking the early establishment phase of the crop. In the Vegetative Growth Stage (January to Late March), the vegetation cover steadily increases, ranging from 10–75%. This phase witness's active growth as the wheat plants flourish with leaves and the canopy expands to encompass more of the soil surface. The Peak Vegetation Cover Stage (April to Early May) signifies the pinnacle of vegetation cover, ranging from 75–100%. At this juncture, the wheat attains its largest canopy size, with near-complete ground coverage. This high percentage epitomizes optimal vegetative growth, crucial for photosynthesis and grain filling. The Reproductive and Maturity Stage (May to Early June) witnesses a decline in vegetation cover, ranging from 50–75% .

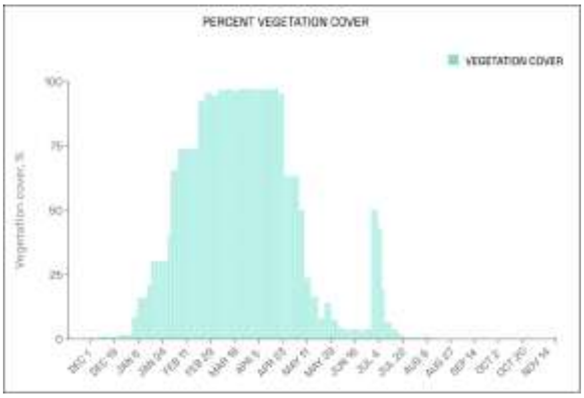

Figure 3. Percent Vegetation Cover Across Different Growing Stages.

The peak vegetation period (March-April) holds particular significance in determining yield potential, as it indicates peak photosynthetic activity and biomass accumulation.

Monitoring Soil Moisture Dynamics in the Root Zone

The Figure 4 and Table 1 illustrates the dynamics of soil moisture within the root zone throughout the growing season for wheat, as monitored by a virtual soil moisture probe. The Figure 4 shows changes from December to harvest, using specific thresholds for soil moisture levels. The soil moisture data provided illustrates the seasonal fluctuations in root zone moisture levels throughout the wheat cultivation cycle and beyond .

In the initial phase of establishment (December 1 to January 15), the soil moisture levels varied from 0.23 to 0.26 m^3/m^3, remaining within the field capacity range. This indicates the presence of sufficient moisture to support early root development without the risk of saturation. The marginal rise in moisture from 0.23 to 0.26 m^3/m^3 implies consistent irrigation and precipitation inputs, reflecting effective water management practices that prevented water stress while avoiding excessive moisture that could impede oxygen availability in the root zone.

Throughout the vegetative growth phase (January 15 to March 15), the soil moisture levels rose to a peak of 0.29 m^3/m^3, nearing the saturation limit. This escalation aligned with the period of maximum evapotranspiration demand due to rapid leaf expansion and photosynthesis. The slight oversaturation noted in mid-March indicates an intensified irrigation regime to meet elevated water demands. While the increased moisture levels supported optimal growth, caution is advised to prevent overwatering, which may result in nutrient leaching and diminished root aeration. In the reproductive phase and harvest preparation stage (March 15 to May 15), the soil moisture levels decreased from 0.29 m^3/m^3 to 0.20 m^3/m^3. This gradual decline mirrors the reduction in irrigation as the crop neared maturity. By early May, the soil moisture levels dipped into the critical zone at 0.20 m^3/m^3, aligning with the goal of minimizing water inputs to avoid delaying grain maturation and facilitate harvesting. The controlled decrease in soil moisture during this period showcases meticulous resource management, ensuring ample residual moisture for grain filling without saturating the root zone. The Saturated Soil Moisture at 0.48 m^3 signifies a level rarely attained, indicating successful avoidance of excessive irrigation or waterlogging throughout the

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cultivation period. Keeping soil moisture below this threshold is vital to ensure plant roots receive adequate oxygen, essential for robust root function and overall plant development. The Field Capacity at 0.32 m^3 epitomizes the optimal soil moisture level for plant water availability, consistently upheld during crucial growth phases. At this level, the soil retains ample water for efficient root uptake without any excess drainage, promoting effective water utilization and fostering robust crop growth.

Figure 4. Virtual Soil Moisture Probe: Monitoring Soil Moisture Dynamics in the Root Zone.

Table 1. Seasonal Soil Moisture Dynamics in the Root Zone

Date (Month)	**Soil Moisture (m^3/m^3)**	**Zone (Interpretation)**
December 1	0.23	Field Capacity
December 15	0.24	Field Capacity
January 1	0.25	Field Capacity (Slight Increase)
January 15	0.26	Approaching Upper Field Capacity
February 1	0.27	High Optimal Range
February 15	0.26	Upper Limit of Field Capacity
March 1	0.28	Approaching Saturation
March 15	0.29	Slight Oversaturation
April 1	0.27	Returning to Field Capacity
April 15	0.25	Optimal Moisture
May 1	0.22	Decreasing Moisture for Harvest

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Date (Month)	Soil Moisture (m^3/m^3)	Zone (Interpretation)
May 15	0.20	Critical Zone Approaching Harvest

The Critical Soil Moisture level at 0.16 m^3 represents the minimum soil moisture threshold where plants start to undergo water stress. These occurrences underscore the significance of timely and sufficient irrigation to avert water stress and maintain crop productivity.

Monitoring Soil Water Potential in the Root Zone

The Figure 5 and Table 2 shows soil water potential dynamics during wheat growing season using a virtual tensiometer from December to harvest. Data is displayed through three indicators: Soil Water Potential Root Zone Combined, Critical, and Field Capacity, offering insights into water availability for crop growth. Root Zone Combined indicates overall water availability in the crop's root zone. Early on, water potential is above critical threshold, providing ample water for establishment. During vegetative growth, fluctuations occur due to plant water uptake and replenishment. Peak vegetation stage sees water potential decrease as demand peaks. Reproductive and maturity stages show temporary stabilization near field capacity as water requirements diminish. At harvest, water potential diminishes as irrigation stops and crop desiccates.

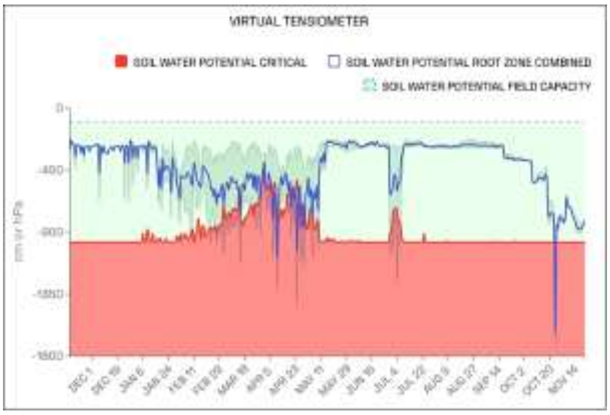

Figure 5. Virtual Tensiometer, Monitoring Soil Water Potential in the Root Zone.

The Soil Water Potential Critical, represented by the red zone, marks the threshold for plant water stress. Soil water potential mostly stays above this level, except briefly during high demand or delays in irrigation, showing effective water management. The Soil Water Potential Field Capacity, shown by the dashed green line, indicates optimal water levels for plant uptake without waterlogging. Irrigation timing is appropriate, with occasional peaks above field capacity due to rainfall or over-irrigation .

Table 2. Seasonal Soil Water Potential Dynamics in the Root Zone Across Growth Stages

Date (Month)	*Soil Water Potential (kPa)*	*Zone (Interpretation)*
December	-300	Field Capacity (Optimal)
January	-400	Field Capacity
February	-450	Optimal for Vegetative Phase
March	-600	Near Upper Limit of Safe Range
April	-700	Approaching Critical Zone
May	-1,000	Critical Zone

Soil moisture levels fluctuated throughout the season, reflecting irrigation events and plant water uptake. The critical soil moisture threshold (0.16 m^3/m^3) was maintained during most growth stages, ensuring optimal conditions for wheat development [20]. Efficient irrigation management ensured that soil moisture rarely exceeded the saturated threshold of 0.48 m^3/m^3, preventing waterlogging [21.[

In December to January, the soil water potential remains above the critical threshold, ensuring sufficient water for crop establishment. From January to Late March, potential fluctuates due to plant water absorption and replenishment. In April to Early May, potential decreases as water demand peaks during rapid crop growth. During the establishment phase (December 1 to January 1), the soil water potential ranges from -300 to -400 kPa, indicating field capacity or optimal moisture conditions for root development. These values suggest that water was readily available for the wheat crop without the risk of oversaturation. This level of moisture supports early root growth and ensures efficient nutrient uptake.

In the vegetative phase (February 1 to March 1), the soil water potential decreases slightly to -450 and -600 kPa, respectively. While these values remain within the safe range for plant growth, they approach the upper limit of optimal soil moisture availability. This decrease indicates increasing water demand due to rapid canopy expansion and higher evapotranspiration rates. Maintaining moisture within this range was crucial to avoid water stress during this critical growth period. The reproductive phase and harvest preparation (April 1 to May 1) show a significant drop in soil water potential to -700 kPa, followed by -1,000 kPa. This marks the transition into the critical zone, where plants begin to experience water stress. The sharp reduction in soil moisture aligns with typical water deficit management practices to support grain ripening and prevent excessive vegetative growth. However, values approaching -1,000 kPa suggest that water availability was minimal, highlighting the need for precise

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timing to balance grain filling and avoid yield penalties .

The diagram 5 illustrates the dynamics of soil water potential over the course of the growing season. Soil water potential is quantified in centimeters (cm) or hectopascals (hPa), with negative values indicating the tension required for plants to draw water from the soil. For context, -1 cm is roughly equivalent to -1 hPa, rendering both units interchangeable in the realm of soil physics. The field capacity (depicted by a dashed line in the green zone) represents the upper threshold of soil water availability, noted at -330 cm (-330 hPa). Throughout the growing season, soil water potential oscillated around this level, showcasing effective irrigation management. This ensures an adequate water supply for plant uptake while avoiding saturation. Nevertheless, intermittent descents below field capacity signal periods of heightened plant water absorption or delayed irrigation responses. The critical threshold for soil water potential (highlighted in red) is identified at -900 cm (-900 hPa). Dropping below this threshold indicates water stress, which can detrimentally impact crop development and yield. Over the season, the soil water potential descended into the critical zone, notably in mid-June, where it plummeted to approximately -950 cm (-950 hPa). These stress occurrences likely correspond to phases of elevated evapotranspiration and insufficient irrigation replenishment, underscoring the necessity for precise scheduling during peak water demand intervals. The collective soil water potential of the root zone (portrayed by the blue line) reflects the genuine moisture dynamics within the root system. For example, in December-January, soil water potential remained relatively stable around -300 cm to -350 cm, as the crop's water requirements were minimal during the establishment phase. As March-April approached, during the vegetative growth phase, soil water potential ranged from -350 cm to -500 cm, indicating heightened water uptake.

Dynamics of Actual Evapotranspiration and Transpiration in Crop Growth

The Figure 6 illustrates the daily fluctuations in actual evapotranspiration (ETa) and transpiration (T) throughout the growing season, measured in millimeters per day (mm/day). The initial phase in December exhibits an ETa rate ranging from approximately 2.0 to 3.0 mm/day, signifying moderate water utilization as the wheat crop progresses in establishing its root system and initial leaf coverage. Transpiration levels remain subdued during this phase primarily due to the limited canopy size, with the majority of water loss occurring through soil evaporation.

Moving into January, as the vegetative phase commences, the ETa escalates to a range of 3.5 to 4.0 mm/day, mirroring the heightened leaf expansion and stomatal activity. Transpiration emerges as the predominant factor in water loss during this period as photosynthesis activity intensifies. The surge in ETa levels underscores the escalating water requirements, underscoring the critical need for timely irrigation to avert water stress. The pinnacle of ETa values is reached in March-April during the late vegetative and reproductive stages, peaking at around 6.0 to 7.0 mm/day. This phase marks the zenith of crop water consumption as the canopy achieves full coverage, resulting in elevated transpiration rates. Effective irrigation management during this critical juncture is imperative to sustain adequate moisture levels and meet the heightened evapotranspiration demands of the crop. As May approaches,

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transitioning into the pre-harvest phase, the ETa diminishes to a range of 4.0 to 5.0 mm/day as water inputs are curtailed to facilitate grain maturation. The decline in ETa aligns with the crop's shift from vegetative growth to reproductive maturation, where irrigation is judiciously limited to prevent delays in ripening while ensuring sufficient moisture for grain filling.

Figure 6. Seasonal Dynamics of Actual Evapotranspiration and Transpiration in Crop Growth

Transpiration also surged, reaching up to 4 mm/day by mid-April, indicating its dominance within ETa as the crop canopy provided ample leaf area for efficient water utilization. During the reproductive and grain-filling stages (April to May), ETa sustained a relatively high level, fluctuating between 4 and 6 mm/day, as the crop maintained substantial water requirements. Transpiration exhibited a similar trend, averaging between 3 and 4 mm/day. Nonetheless, intermittent declines in both ETa and T in late May and June imply instances of water stress, potentially stemming from inadequate irrigation or elevated evapotranspiration rates. Prolonged periods of such stress could adversely affect crop yield. ETa peaked during the vegetative and reproductive stages, reaching up to 6.5 mm/day in early April. Transpiration dominated during this phase, indicating efficient water utilization by the crop canopy [22]. Late-season declines in ETa and transpiration reflected reduced water demand during crop senescence [23.[

The monitoring of actual evapotranspiration and transpiration across the growing season offers valuable insights into crop water utilization and irrigation efficiency. During the peak growth period, ETa peaked at 6.5 mm/day, with transpiration contributing up to 4 mm/day. Instances of water stress, indicated by declines in ETa and T, underscore the necessity for precise irrigation management. These discoveries underscore the significance of real-time monitoring by Irriwach System and adaptive irrigation strategies to boost water utilization efficiency and bolster optimal crop performance.

Correlation between Air Temperature and Cumulative Growing Degree Units (GDU(

The relationship between air temperature and cumulative GDU is critical for understanding the wheat crop's development. Cool early-season temperatures support establishment and vernalization, while rising spring and summer temperatures drive active growth and reproductive processes. Monitoring these variables provides insights into developmental stages, enabling optimized irrigation, fertilization, and management practices while mitigating risks from extreme temperatures. Achieving an adequate heat accumulation while avoiding stress from high temperatures is crucial for maximizing yield and quality.

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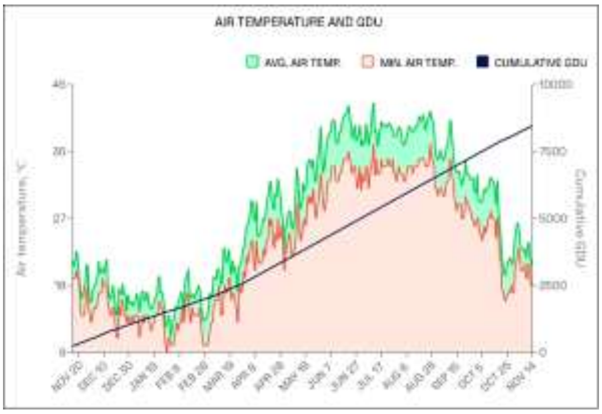

Figure 7. illustrates the correlation between Air Temperature and Cumulative Growing Degree Units (GDU) Throughout the Growing Season.

Figure 7 depicts the interplay among Average Air Temperature (Avg. Air Temp.), Minimum Air Temperature (Min. Air Temp.), and Cumulative Growing Degree Units (GDU) over the wheat growing season, underscoring the impact of temperature and heat accumulation on crop growth and development. During the initial growth phase (December to February), average air temperatures range between 10–18°C, while minimum temperatures oscillate around 9–12°C. Throughout this period, cumulative GDU increases gradually, reaching approximately 500–1,000 GDUs by the conclusion of February, reflecting the decelerated crop development under lower temperatures. In the vegetative growth phase (February to April), average temperatures ascend to 18–27°C, while minimum temperatures elevate to 15–20°C. The warmer conditions expedite the accumulation of GDUs, which culminate at approximately 2,500–3,000 GDUs by the end of April. This stage is characterized by rapid vegetative growth, with leaves and the crop canopy expanding significantly. The augmented heat units play a pivotal role in supporting this active growth phase. Throughout the reproductive and grain-filling stages (April to May), both average and minimum air temperatures peak. Average temperatures fluctuate between 27–36°C, with minimum temperatures ranging from 20–28°C. The sharp incline in the cumulative GDU curve, exceeding 5,000–6,000 GDUs by early June, mirrors the substantial heat accumulation necessary for flowering, grain filling, and other reproductive processes .

The rate of GDU accumulation decelerates significantly, with the cumulative total reaching a plateau of approximately 9,000–10,000 GDUs by the end of the growing season. The correlation between air temperature and cumulative GDU is pivotal for comprehending the wheat crop's development. Chilly early-season temperatures bolster establishment and vernalization, while ascending spring and summer temperatures propel active growth and reproductive processes. Monitoring these variables furnishes insights into developmental stages, enabling optimized irrigation, fertilization, and management practices while mitigating risks from extreme temperatures. Attaining adequate heat accumulation while averting stress from high temperatures is paramount for maximizing yield and quality [24.[

Leaf Nitrogen Dynamics and Cumulative

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The Figure 8 shows Leaf Nitrogen (%) and Cumulative Crop Nitrogen Uptake (kg/ha) dynamics from December to harvest, revealing nitrogen uptake patterns and utilization throughout the growth cycle. During December to February, nitrogen uptake is gradual as the wheat crop focuses on root system establishment. Leaf nitrogen levels are low, reflecting minimal nitrogen demand. Adequate nitrogen is crucial for early development and subsequent growth phases. Upon entering the vegetative growth stage (February to April), there is a significant increase in both leaf nitrogen content and cumulative nitrogen uptake. This phase coincides with rapid canopy expansion, during which nitrogen plays a crucial role in supporting photosynthesis, protein synthesis, and overall biomass accumulation. The substantial rise in cumulative nitrogen uptake highlights the crop's heightened nitrogen demands, making this stage essential for nitrogen fertilization to sustain vigorous growth.

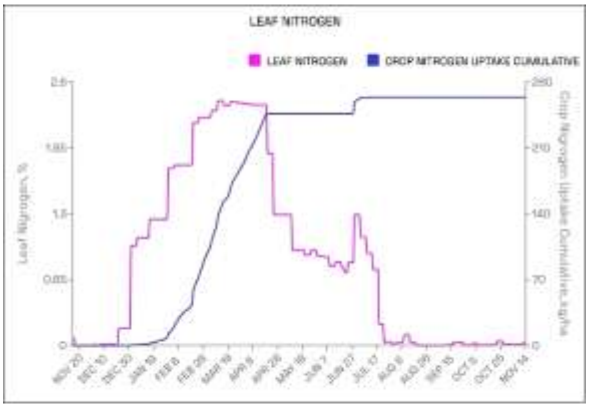

Figure 8. Spectral signature of Leaf Nitrogen Dynamics and Aggregate Crop Nitrogen Uptake Throughout the Growing Season.

As the transition to the reproductive stage progresses (March to April), leaf nitrogen levels reach their peak before gradually decreasing. This decline is a result of the redistribution of nitrogen from vegetative tissues to the developing grains. Throughout this period, nitrogen is reallocated to promote grain filling and protein synthesis, ensuring the crop's reproductive success. From December to harvest, nitrogen uptake and utilization are crucial for wheat growth. Effective nitrogen management ensures high yields and grain quality. Understanding these dynamics helps optimize fertilization, reduce nitrogen loss, and enhance efficiency. The graph shows Leaf Nitrogen (%) and Cumulative Crop Nitrogen Uptake (kg/ha) from December to harvest. These metrics highlight important stages in nitrogen uptake and utilization.

During the initial stage (December to February), leaf nitrogen levels commence at approximately 0% and incrementally ascend to around 0.6–0.7% by February's denouement. This signifies minimal nitrogen assimilation as the crop directs its focus towards root system establishment. Cumulative nitrogen uptake remains modest during this period, reflecting the crop's constrained nutrient demand .

In the vegetative growth stage (February to April), leaf nitrogen witnesses a significant escalation, culminating at approximately 2.5–2.6% by late March to early April. This sharp upsurge aligns with the crop's heightened nitrogen demand during canopy development and photosynthesis. Throughout this phase, cumulative nitrogen uptake escalates rapidly, reaching approximately 70–80% of the total by April's closure. This period proves pivotal for nitrogen fertilization to sustain the crop's progression. The onset of the reproductive growth phase (April to May) initiates a downturn in leaf nitrogen, plummeting to around 1.5–2.0% by late May. This descent mirrors the redistribution of nitrogen from vegetative tissues to the burgeoning grains. Cumulative nitrogen uptake approaches 90–95% of its total during this phase, indicating that the crop's nitrogen absorption is nearing its culmination. Cumulative nitrogen uptake stabilizes at 100% of its total by late June, signaling the cessation of active nitrogen absorption from the soil. These percentages proffer invaluable insights for optimizing nitrogen use efficiency and ameliorating wheat production outcomes.

Carbon Supply, and Soil Organic Matter (SOM) Change During the Growing Season

Figure 9 illustrates the fluctuations in Net Carbon Supply in Soil (%), Net Carbon Supply in Soil Cumulative (mg/kg), and Soil Organic Matter (SOM) Change Cumulative (mg/kg) from the commencement of the growing season in December until the harvest period.

In the initial phase (December to late February), the net carbon supply in soil commences at nearly 0% and gradually ascends to approximately 20–30% by late February. This signifies the initial influx of carbon stemming from early root activity and microbial processes. Throughout the vegetative stage (March to April), the net carbon supply experiences a rapid surge, reaching its peak at 100% by early May as carbon contributions from crop roots, residues, and microbial activity peak. The Net Carbon Supply in Soil Cumulative (mg/kg) initiates at 0 mg/kg in December and steadily escalates throughout the season. By late April, around 70–80% of the total cumulative carbon supply is attained, primarily fueled by the active growth phase of the crop. By the time of harvest in late June, the cumulative carbon supply stabilizes at its maximum value of approximately 2200 mg/kg, reflecting the complete carbon integration into the soil during the season.

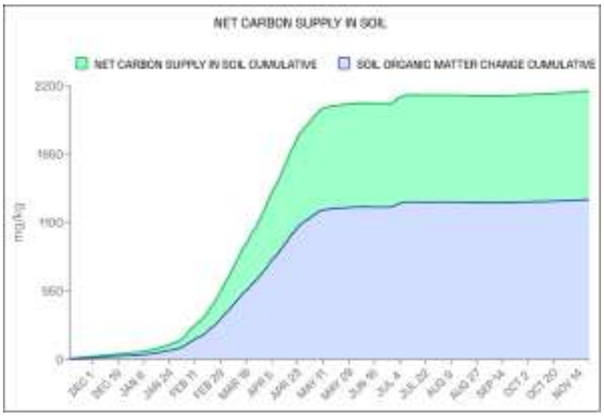

Figure 9. Fluctuations in Net Carbon Supply, Cumulative Carbon Supply, and Soil Organic Matter (SOM) Change During the Growing Season

The Soil Organic Matter (SOM) Change Cumulative (mg/kg) commences at 0 mg/kg in December and progresses gradually during the early stages of crop growth. By late February, the cumulative SOM reaches approximately

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20–30% of the total seasonal value. From March to late April, the SOM change accelerates, achieving 60–70% of its total value by the end of April, as enhanced microbial decomposition and carbon input stabilize organic matter. By harvest time (June to July), the cumulative SOM reaches 100%, stabilizing at approximately 1650 mg/kg, indicating the net seasonal increase in organic matter.

Figure 9 illustrates the fluctuations in Net Carbon Supply in Soil (%), Net Carbon Supply in Soil Cumulative (mg/kg), and Soil Organic Matter (SOM) Change Cumulative (mg/kg) from the commencement of the growing season in December until the harvest period.

In the initial phase (December to late February), the net carbon supply in soil commences at nearly 0% and gradually ascends to approximately 20–30% by late February. This signifies the initial influx of carbon stemming from early root activity and

achieving 60–70% of its total value by the end of April, as enhanced microbial decomposition and carbon input stabilize organic matter. By harvest time (June to July), the cumulative SOM reaches 100%, stabilizing at approximately 1650 mg/kg, indicating the net seasonal increase in organic matter.

Date (Month)	*Cumulative Precipitation (mm)*	*Cumulative Irrigation (mm)*	*Cumulative ETa (mm)*
December	10	0	15
January	15	50	70
February	20	150	170
March	30	300	320
April	40	500	520
May	40	750	770

microbial processes. Throughout the vegetative stage (March to April), the net carbon supply experiences a rapid surge, reaching its peak at 100% by early May as carbon contributions from crop roots, residues, and microbial activity peak. The Net Carbon Supply in Soil Cumulative (mg/kg) initiates at 0 mg/kg in December and steadily escalates throughout the season. By late April, around 70–80% of the total cumulative carbon supply is attained, primarily fueled by the active growth phase of the crop. By the time of harvest in late June, the cumulative carbon supply stabilizes at its maximum value of approximately 2200 mg/kg, reflecting the complete carbon integration into the soil during the season. The Soil Organic Matter (SOM) Change Cumulative (mg/kg) commences at 0 mg/kg in December and progresses gradually during the early stages of crop growth. By late February, the cumulative SOM reaches approximately 20–30% of the total seasonal value. From March to late April, the SOM change accelerates,

During the initial stage (December to February), both net carbon supply and SOM change are minimal, commencing at 0%. Limited root activity and microbial processes result in low carbon inputs and organic matter stabilization. By late February, net carbon supply and SOM change reach 20–30%, reflecting early contributions from root exudates and microbial activity. The vegetative growth phase (March to April) witnesses the most substantial increase in net carbon supply and SOM change. Net carbon supply peaks at 100% by late April, signifying active contributions from plant residues, root exudates, and microbial biomass .

The outcomes illustrate that carbon inputs and organic matter stabilization are intricately linked to the crop's growth cycle. The

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vegetative phase (March to April) emerges as the most crucial period for carbon input, accounting for 70–80% of the cumulative supply by late April. Similarly, SOM change mirrors these inputs, with 60–70% of the total stabilization occurring during the same phase. By harvest time, the soil achieves a net carbon supply of 2200 mg/kg and an organic matter gain of 1650 mg/kg, showcasing the advantages of effective carbon inputs throughout the growing season. These findings underscore the significance of managing crop residues and microbial processes to enhance soil health and carbon sequestration, thereby ensuring sustainable agricultural practices.

Cumulative trends of Precipitation, and Irrigation Amount

The Figure 10 and Table 3 illustrates the cumulative trends of Precipitation (depicted by the green line .(

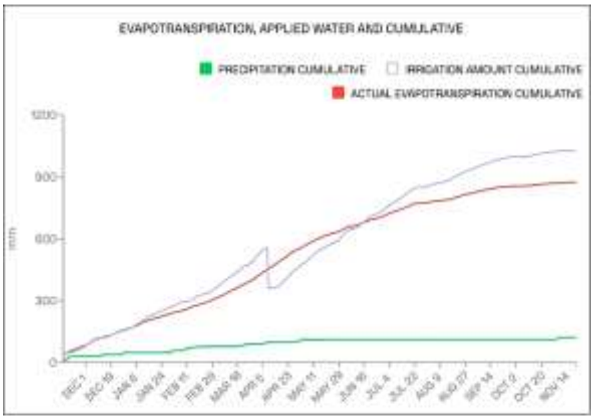

Figure 10. Cumulative Evapotranspiration, Precipitation, and Irrigation Amounts During the Growing Season

The cumulative ETa closely follows the cumulative irrigation, indicating effective water use. The total ETa reaches approximately 950 mm, reflecting the water lost through both soil evaporation and crop transpiration. The ETa line plateauing post-harvest confirms that crop water use drops to minimal levels after the harvest period.

Precipitation remains relatively low throughout the crop cycle, totaling around 70 mm for the entire season. This indicates that natural rainfall only contributed a minute portion of the total water required by the crop.

Irrigation inputs start to escalate notably in January, reaching their peak between March and May (with values soaring to 750–850 mm), and then stabilize after June as the crop nears harvest and water inputs are diminished. The total cumulative irrigation for the season amounts to approximately 850 mm, highlighting a substantial dependence on supplemental irrigation to bolster crop growth.

The cumulative ETa closely mirrors the cumulative irrigation, signifying efficient water utilization. The total ETa reaches close to 950 mm, representing the water lost through both soil evaporation and crop transpiration. The ETa curve leveling off post-harvest confirms that crop water usage dwindles to minimal levels after the harvesting period

By late February, precipitation contributes to approximately 15–20% of the total seasonal water input. Throughout the vegetative phase

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(March to April), precipitation continues to rise, accounting for around 20–30% of the total seasonal water input by late April, underscoring the necessity for supplementary irrigation. The blue line delineates the cumulative irrigation, which initiates post the crop's establishment phase. By late February, irrigation constitutes about 10–15% of the seasonal total. The graph depicts a notable surge in irrigation during the vegetative and reproductive phases (March to April), effectively meeting the water demands of the burgeoning crop .

The red line, portraying cumulative actual evapotranspiration (ETa), signifies the crop's water consumption via evaporation and transpiration. ETa commences at 0 mm in December and gradually escalates during the initial growth phase, reaching approximately 15–20% of the seasonal total by late February. The ETa curve ascends steeply during the vegetative phase (March to April), mirroring the crop's heightened water demand during active growth. By late April, ETa constitutes 70–80% of the seasonal total, culminating at 100% by harvest, signifying the fulfillment of the total seasonal water demand .

The Figure 10 accentuates the pivotal equilibrium between precipitation and irrigation in meeting evapotranspiration requisites. While precipitation assumes a crucial role in the initial growth stages, the dependency on irrigation intensifies significantly during the vegetative and reproductive phases. The convergence of cumulative applied water (precipitation + irrigation) with cumulative ETa demonstrates the effective management of the crop's water requirements throughout the growing season, ensuring optimal growth and water use efficiency.

Dry Matter Production (kg/ha(

The Figure 11 illustrates the cumulative trends in Dry Matter Production (kg/ha) across three scenarios: Attainable Crop Growth, Water Unlimited Crop Growth, and Cumulative Crop Growth throughout the growing season, commencing in December and concluding at harvest. The Attainable Crop Growth (depicted by the green line) initiates at 0 kg/ha in December and experiences a rapid escalation during the vegetative phase. By late April, it reaches approximately 21,000–23,000 kg/ha, signifying the crop's maximum potential under prevailing conditions. The growth persists steadily and stabilizes at its zenith of 28,000 kg/ha by harvest, showcasing the utmost growth achievable when key limiting factors are minimized. The Water Unlimited Crop Growth (represented by the orange line) also commences at 0 kg/ha and ascends significantly during the vegetative stage. By late April, it attains around 19,000–21,000 kg/ha, slightly below attainable growth, as factors beyond water availability (e.g., nutrients or temperature) constrain potential growth. By harvest, cumulative growth under water unlimited conditions stabilizes at 25,000 kg/ha, accentuating the influence of optimal water supply but with constraints posed by other environmental or managerial factors. The Cumulative Crop Growth (illustrated by the blue line), reflecting actual field conditions, commences similarly at 0 kg/ha and rises steadily throughout the vegetative phase. By late April, cumulative growth reaches 18,000–19,000 kg/ha, slightly trailing water unlimited growth due to suboptimal water, nutrient availability, or environmental conditions. Growth stabilizes at approximately 22,000 kg/ha by harvest, demonstrating the combined effects of real-world limiting factors on biomass production. During the initial stage (December to

February), dry matter production remains minimal across all scenarios as the crop focuses on root establishment and early vegetative growth, with growth below 1,000 kg/ha, reflecting the gradual accumulation of biomass.

The vegetative growth phase (February to April) marks the period of most significant biomass accumulation. Attainable growth reaches approximately 21,000–23,000 kg/ha by late April, while water unlimited growth peaks at 19,000–21,000 kg/ha, and cumulative growth lags slightly at 18,000–19,000 kg/ha. This phase underscores the crucial importance of water and nutrient availability for maximizing crop growth potential.

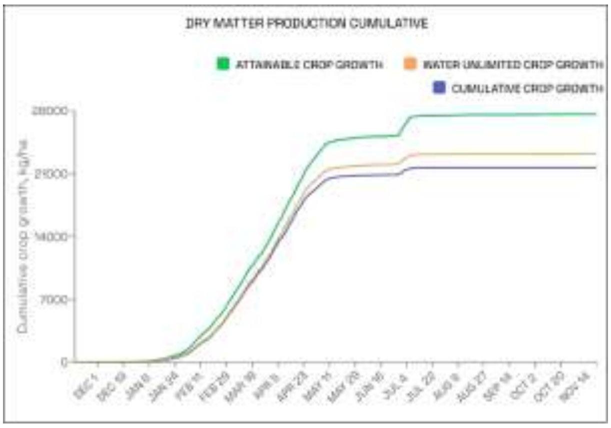

Figure 11. Dry Matter Production (kg/ha) Across Attainable, Water-Unlimited, and Cumulative Crop Growth Throughout the Growing Season

During the reproductive phase and maturity stage (April to May), growth begins to stabilize as the crop prioritizes grain filling over biomass accumulation. Attainable growth reaches its peak of 28,000 kg/ha, water unlimited growth stabilizes at 25,000 kg/ha, and cumulative growth reaches 22,000 kg/ha, showcasing the cumulative impact of environmental and managerial constraints. In the post-harvest period (July to November), all growth trajectories remain constant, reflecting the final dry matter production for the season. The disparities between the scenarios emphasize the potential gains achievable under ideal conditions (attainable growth) versus the restrictions of real-world conditions (cumulative growth). In conclusion, the graph accentuates the impact of water availability, nutrient management, and other environmental factors on cumulative dry matter production. The vegetative phase emerges as the most critical period for biomass accumulation, contributing approximately 70–80% of the total growth by late April. While attainable growth reaches 28,000 kg/ha, water unlimited growth attains 25,000 kg/ha, and cumulative growth stabilizes at 22,000 kg/ha by harvest. These findings underscore the significance of effective water and nutrient management in maximizing crop growth and yield under field conditions.

Cumulative dry matter production under field conditions reached 22,000 kg/ha by harvest. Attainable growth, under ideal conditions, peaked at 28,000 kg/ha, highlighting the potential gains achievable with improved water and nutrient management [25].

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Conclusion

The in-depth analysis of the wheat growing season in Karbala province highlights the intricate interplay of various factors such as vegetation cover, soil moisture, evapotranspiration, nutrient uptake, carbon dynamics, and environmental conditions in influencing crop development and yield.

The results indicate that shifts in vegetation cover correspond to significant growth phases, with the peak canopy cover observed in March-April playing a pivotal role in optimizing photosynthesis and biomass accumulation. The dynamics of soil moisture and water potential underscore the critical need for precise irrigation management to meet water requirements during crucial growth stages, especially at peak vegetation and reproductive phases. Effective irrigation techniques have successfully minimized waterlogging and water stress, ensuring optimal moisture levels in the root zone.

The trends in actual evapotranspiration highlight the changing water needs of the crop, with the highest demand occurring during vegetative and reproductive stages. Monitoring temperature variations and cumulative growing degree units (GDUs) offers valuable insights into growth stages and aids in implementing strategies to alleviate heat stress. The nitrogen dynamics emphasize the significance of timely fertilization to support vegetative growth and facilitate efficient redistribution during grain filling. Analyses of carbon and organic matter showcase the role of root exudates and microbial activity in enhancing soil health and promoting carbon sequestration. Lastly, the assessment of dry matter production underscores the potential for enhancing yields through optimized water and nutrient management practices.

Recommendations

1- Optimized Irrigation Scheduling
Implement real-time soil moisture and water potential monitoring to adjust irrigation precisely during peak demand periods. Automating irrigation systems based on virtual probes can enhance water use efficiency and prevent stress or over-irrigation.

2- Temperature and GDU Monitoring
Utilize temperature and GDU data to identify critical growth windows. Implement measures to mitigate heat stress during reproductive phases, such as Irrigation or adjusting planting dates.

3- Carbon and Organic Matter Enhancement
Promote practices like crop residue retention and cover cropping to boost soil organic matter and carbon sequestration. These approaches will improve long-term soil health and sustainability.

4- Yield Gap Reduction
Address factors limiting cumulative dry matter production by enhancing water and nutrient availability, particularly during the vegetative

phase. Adopting best management practices can bridge the gap between attainable and actual growth under field conditions.

5- Integrated Monitoring Systems

Deploy Irriwch Technique to integrated monitoring systems combining data on soil, water, nutrients, and climatic factors. These systems will provide actionable.

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