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Improving the Conversion Efficiency of Photosynthetically Active Radiation (PAR) Absorbed by Winter Wheat Under Deficit Irrigation Using Cost-Effective Autonomous IoT Devices

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Abstract

Water shortage is considered the most critical issue in the regions of arid and semi-arid climate, which is affecting the growth cycle and yield of the winter wheat crop (Triticum durum Desf.). Consequently, irrigation is necessary to increase crop production and maximize water use efficiency (WUE). This study was carried out over three consecutive cropping seasons (2021-2022), (2022-2023), and (2023-2024) at the Research Unit of the National Institute of Rural Engineers, Water and Forests (INRGREF) at Cherfech. This study was aimed at examining the impact of three levels of continued deficit irrigation (D1 = 75% ETc, D2 = 60% ETc, and D3 = not irrigated only by rainfall) on leaf area index (LAI), water consumption (WC), photosynthetic active radiation absorbed (PARabs), radiation use efficiency of grain yields (RU_{EY}), and the relationship between cumulative WC and cumulative PAR_{abs}. The cost-effective and precise autonomous Internet of Things device with artificial intelligence at the edge was utilized to monitor irrigation and crop water consumption. At harvest, a decrease in TPDM was registered in the two treatments, DI2 and DI3, by (30.2%; 29%) and (40%; 38.7%) in 2020-2021, (14.7%; 12.3%) and (32%; 30.1%) in 2022-2023, and (19.7%; 14%) and (38%; 34.1%) in 2023-2024, when contrasted with the respective DI1 and FI treatments, respectively. During the three-cropping season (2021-2024), ANOVA analysis revealed that DI and FI treatments were not significantly affected ($P > 0.05$) by the accumulated PARabs. The cumulative PARabs in D2 and D3 were dropped to 1.7% and 4.9%, respectively, compared to FI. In the second season (2022-2023) and in the third season (2023-2024), the PARabs in D2 and D3 decreased by (4 - 4.9%) and (15.7 - 15.8%), respectively, compared with FI. The lowest GY was registered under a rainfed treatment, and it decreased from 64.5 to 68.6% in the three experiments compared to FI. The highest RUEY was registered in FI. There was a reduction in D1 and D2 in the first season of 6.6% and 51.9%, respectively, compared with FI. Under the treatment D2 at the second and third seasons, the RUEY decreased from 28.6 to 43% compared to the control treatment. Photosynthetically active radiation (PARabs) and crop water consumption (CWC) have a strong linear relationship; this relationship can be used to estimate crop water requirements as a simple measure of cumulative radiation absorbed (cereal crops).

Keyword: durum wheat, water deficit, water use efficiency, radiation use efficiency, grain yield, total produced dry matter

1. Introduction

Winter wheat is produced around the world, particularly in the Mediterranean Basin, which is recognized as the focal point for its cultivation (Royo et al., 2014; Bonjean et al., 2016). Furthermore, climatic data analysis suggests that agricultural crops in the Mediterranean region will be at risk of yield reduction due to a hotter and drier climate (Ceglar et al., 2021; Ferrise et al., 2011). In the Mediterranean region, Tunisia is recognized as a significant center of winter wheat (Ayed & Amara, 2009). Over the past years, rainfall was insufficient, coupled with elevated temperatures during the critical stages of crop development. These severe drought conditions, which have not been experienced in the region for more than 20 years, severely affected crop growth, leading to widespread crop failures. Consequently, 2023 wheat production in Tunisia was estimated at 400,000 tons, around 65 percent lower than average (FAO, 2023). Despite this current climatic situation, the country still aims to increase wheat production. A subsidy for irrigation water and technical support for farmers growing wheat in irrigated areas are two of the government's policy tools (FAO, 2023). The irrigation volume and frequency of winter wheat are mainly affected by several factors, including regional climatic parameters, water availability, type and properties of soil, and physiological crop characteristics (Asmamaw et al., 2023; Dhayal et al., 2023; Zhang et al., 2023). The responses of winter wheat under seasonal drought conditions integrate the influence of multiple physiological parameters. Water stress mainly affects photosynthesis, respiration, and transpiration (Feret et al., 2019; Stimson et al., 2005), which consequently affects the growth cycle of the crop, production, and quality attributes (Zhang et al., 2021; Zhuang et al., 2020). Moreover, crop biomass production depends on the canopy's ability to convert incoming photosynthetically active radiation (PAR, 400-700 nm) into new biomass by intercepting it. This process is based on the canopy structure and leaf area index (LAI) (Sinclair & Muchow, 1999). The slope of a linear relationship between PAR and the accumulated dry matter is defined as the radiation use efficiency (RUE) (Monteith, 1977; Tesfaye et al., 2006). RUE values have been reported to range from 1.46 to 3.50 g MJ^{-1} for winter wheat and from 1.3 to 2.52 g MJ^{-1} for barley under drought stress conditions, based on PAR measurements conducted under non-stress conditions (Jamieson et al., 1995). This reduction in RUE is due to a progressive decline in effective photosynthesis, caused by minimizing intercepted PAR as a result of reduced leaf area (Wilson & Jamieson, 1985). However, practicing deficit irrigation (DI) offers an alternative strategy of water management, enabling the irrigation of larger cultivated areas despite a lack of water resources (Sezen et al., 2014; Fereres & García-Vila, 2019). The use of this technique has a considerable effect on irrigation planning as plants respond differently to drought stress across various growth stages, with minimal effect on overall yield. An important factor in its application is determining the right time and degree of water stress imposed on crops (Jovanovic & Stikic, 2012; Yang et al., 2017). To effectively implement the DI, incorporating smart irrigation technologies such as the smart tensiometers becomes essential, and by integrating the water requirement, measured from the data acquired by the tensiometers, with PAR data, it becomes possible to tailor the water needs of crops throughout their growth stages. These smart tensiometers can be controlled through an IoT device network (Obaideen et al., 2022). In the context of an IoT-based precision irrigation system, Zhang et al. (2022) demonstrated a system based on real-time soil monitoring sensing and Long-Range Wide Area Network (LoRaWAN) communication technology. This research focuses on the effects of the use of IoT Devices under deficit irrigation, on: (i) leaf area index (LAI), (ii) photosynthetically active radiation absorbed (PARabs) and (iii) radiation use efficiency (RUE). A relationship between PAR and crop water requirements will be explored, mainly to facilitate the estimation of winter wheat's water needs based on Total PAR abs measured.

2. Materials and Methods

2.1 Description of the Experimental Site

Three consecutive cropping seasons (2021-2024) were used for field experimental works at the National Research Institute for Rural Engineering, Water, and Forestry (INRGREF) experimental unit in Cherfech (Lat. 37.1°N; Long. 10.5°E, Alt. 328 m a.s.l.). The study was conducted in an area with a semi-arid climate, minimum and maximum air temperatures ranging from 6 to 19 °C and 15.7 to 33.5 °C, respectively. 1100 mm of evapotranspiration (ET0) and 450 mm of precipitation were averaged annually. The temperature varied from 17 to 35 °C, from 15 to 23 °C, and from 13 to 26 °C in the first, second, and third crop seasons, respectively. Furthermore, there was the strongest correlation between the two climatic parameters, with daily ET0 and Tavg roughly following the same pattern throughout the growing season. With totals of 187, 215, and 183 mm, cumulative precipitation during the winter wheat seasons was comparable and mostly fell during the winter (Belkher et al., 2025).

2.2 The Plant Material

Plant material of the experiments contained two local durum wheat varieties. While the "Razek" variety was used in the following two cropping seasons, on November 21, 2022 and December 5, 2023. "Maali" variety was planted during the first cropping season November 26, 2021. Mechanically wheat seeds were sown, with a seeding rate of 150 kg ha^{-1}. Di-ammonium phosphate $(NH4)_2HPO4$ (DAP) was utilized by 150 kg ha^{-1} before sowing in all three cropping seasons. The application of 150 kg ha^{-1} of seasonal ammonium nitrate was made in three stages: 30% (at the 3-leaf stage), 40% (at tillering), and 30% (at booting). The controlling pest and weed was executed according to local procedures. The exchangeable phosphorus was at the level of 81 parts per million; texture was classified as clay loam, whereas, 0.2%, 0.7%, and 1.2% are pointed to the total exchangeable potassium, organic carbon, and organic matter in the soil samples, respectively. Richard's device was utilized to measure soil moisture at wilting point and field capacity. Samples were collected from three soil profiles with depth 10-60 cm. Water content at field capacity (θfc) and wilting point (θwp) were varied between 42.9%, 45.9% and 26.1%, 28.2%, respectively. There are 172 mm m^{-1} of total plant-available water (TAW). The apparent density averaged between 1.60 to 1.67 from the soil surface to a depth of one meter (Belkher et al., 2025).

2.3 Experimental Design and Treatments

Four levels of irrigation were applied with three times replication. The irrigation treatments included full irrigation (FI), where crops were irrigated at 100% ETc (crop evapotranspiration); two deficit irrigation (DI) treatments, D1 (DI-75%) and D2 (DI-60%), where crops were irrigated at 75% and 60% of ETc, respectively; and a rainfed treatment, D3. In this experiment, a randomized block design was approved with 12 plots in total, covering an area of 16 m^2 for each (Figure 1). A drip system was applied to irrigate all plots using surface drip laterals with 0.5 m of row spacing. The inline drippers, spaced 0.33 m apart, emitted 4 l h^{-1} with a fixed pressure of 1 bar. The irrigation water had an electrical conductivity (ECw) of 3.12 dS m^{-1}.

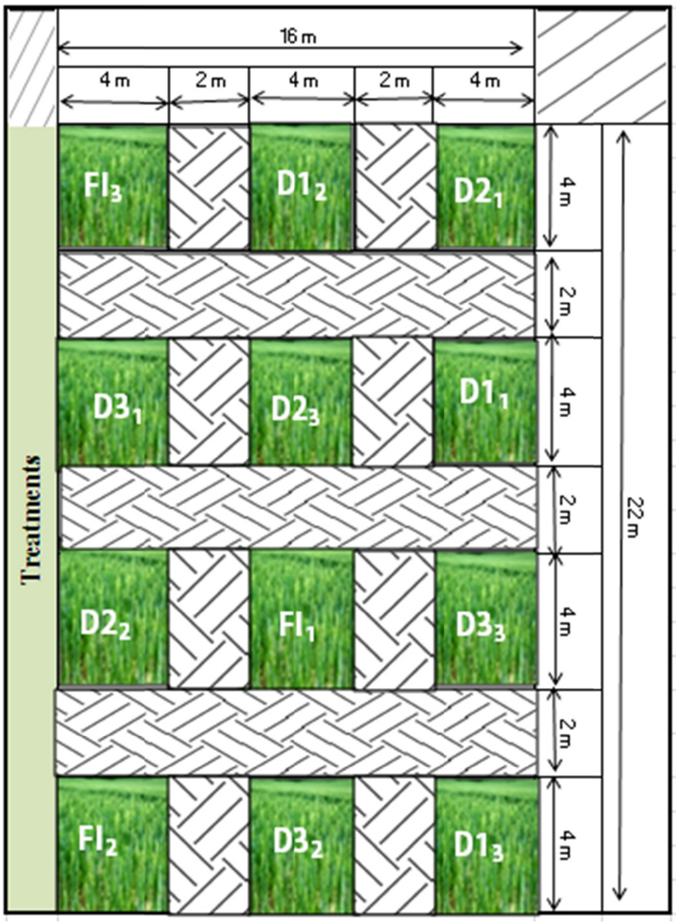


Figure 1. Experimental design and treatments with repetitions

The crop water requirements are represented by the crop evapotranspiration ETc, which can be computed using the FAO-56 single crop coefficient method. Initial, mid-, and end-season crop coefficient (Kc) values were 0.7, 1.15, and 0.3, respectively (Allen et al., 1998). The Penman-Monteith model was used to calculate the reference evapotranspiration (ET0) on daily basis.

$$ET_c = K_c \times ET_0 \quad (1)$$

The soil water balance equation, as described by Hillel (1998), was used to estimate water consumption:

$$WC = P + I + U + R - Dw - \Delta S \quad (2)$$

where, P represents effective precipitation (mm), I is the irrigation (mm), U refers to the upward capillary flow into the root zone (mm), R is the runoff (mm), D is the downward drainage out the root zone (mm), and ΔS is the change of soil water stored in the 0-60 cm soil layer (mm). The upward and downward flow was estimated using Darcy's law (Kar et al., 2007; De Medeiros et al., 2005). The results indicated that both upward and downward flow were negligible at the experimental site. Similarly, runoff was insignificant across all three growing seasons. Soil water content was monitored using a smart tensiometer every 15 minutes and gravimetrically every seven days. Measurements of soil water content were collected at 20 cm depth intervals.

2.3 Smart Tensiometers of the Study (Soil Water Status)

In this study the smart tensiometer being used was developed as part of the Osirris TUNGER 2+2 projects, which was a bilateral partnership between Tunisia and Germany. The presentation of smart tensiometer, WaziSense, WaziCloud server as well as the platform and them technical details were described by (Belkher et al., 2025).

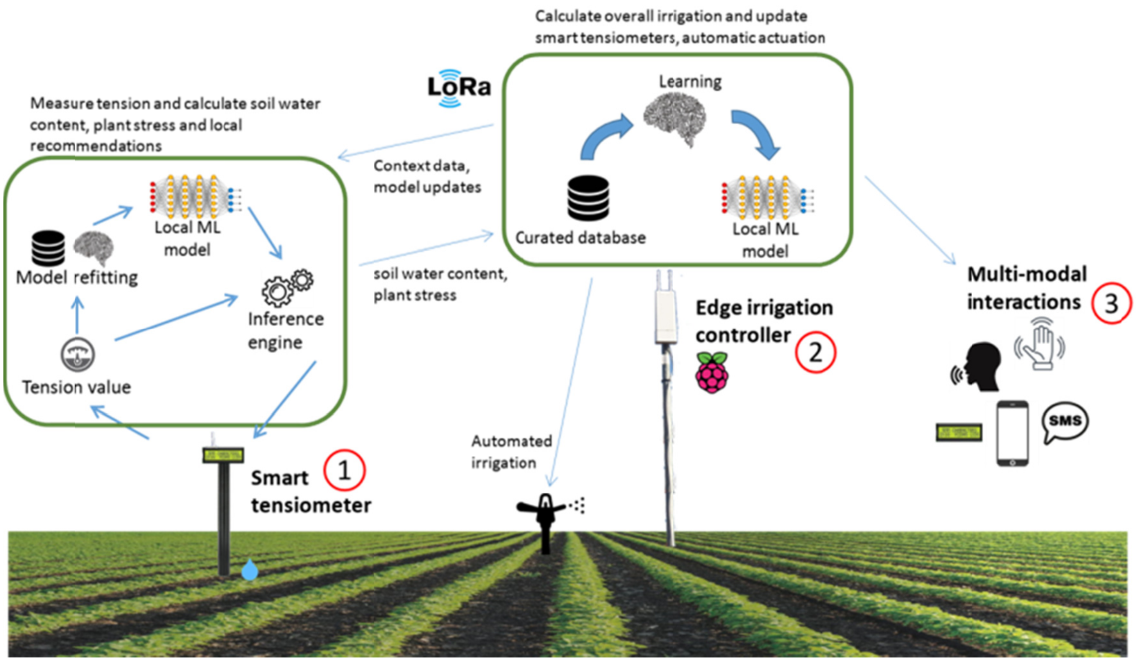


Figure 2. Smart tensiometer through precise irrigation management platform system (Osirris project)

Source: https://www.waziup.org/research-innovation/projects/osirris

2.4 Measurement of Soil Water Status

The gravimetric method to measure the soil moisture content on a weekly basis was used during the 2021-2022 cropping season. For each plot, soil samples were collected at three different depth of: 0-20, 20-40, and 40-60 cm. After the samples were dried for 24 hours at 105 °C in an oven, the root zone area soil moisture content was estimated. The soil water matric potential in the root zone was continuously and in real time monitored for the next two crop seasons (2022-2023) and (2023-2024) using four smart tensiometers called "WaziSense". These tensiometers were placed 20 cm, 40 cm, and 15 cm from the emitter in two fully irrigated plots. In addition to the smart tensiometric method soil moisture content was gravimetric calculated in the depth ranging from 0 to 60 cm. Samples were taken at 20 cm intervals, and oven drying was used for analysis. The soil water retention curve was created using information gathered during the 2022-2023 cropping season, including soil matric potential and soil moisture contents (Belkher et al., 2025).

2.5 Plant Sampling and Measurement

2.5.1 Total Dry Matter Production and Grain Yield

Representative plant samples were collected using a destructive sampling technique over the course of the three growing seasons. A random 1 m^2 section of wheat was selected for sampling in each subplot. A digital scale was then used to determine the fresh weight of the plant parts after they had been separated into stems, leaves, and spikes. After being packed in kraft paper bags, each plant part was dried for 48 hours at 70 °C in an oven until its weight stabilized. The dry weights of each plant part were added to determine the total produced dry matter (TPDM). Grain yield (GY) per hectare was computed after the wheat kernels were harvested, separated from the spikes, and weighed.

2.5.2 Measurement of LAI and of the PAR_{abs}

For measuring photosynthetically active radiation (PAR) and canopy structure effectively, the SunScan Canopy Analysis System (Type SS1) was utilized. Rapid spatial averaging over wide areas is made possible by its 1-meter probe. Two metrics were measured in this study using the SunScan system: photosynthetically active radiation absorbed (PARabs) and leaf area index (LAI).

LAI was measured, directly by the SunScan, at specific intervals throughout the crop growth cycle during three cropping seasons under four water treatment conditions (FI, D1, D2, and D3).

The Beer (Manrique et al., 1991) formula can be used to calculate PAR_{abs}:

$$PAR_{abs} = 0.5 \times R \times FI \quad (3)$$

Throughout the season, PAR (MJ m^{-2} d^{-1}) values were taken at the top and bottom of the wheat canopy at regular intervals using the SunScan. According to Monteith (1981), the fraction intercepted PAR (FI) was computed as follows:

$$FI = \frac{I_0 - I}{I} \quad (4)$$

where, I_o represents the incident PAR at the top of the canopy, I represent the transmitted PAR at the bottom, and R represents the daily global radiation (MJ m^{-2} d^{-1}).

2.6 Radiation Use Efficiency (RUE)

The efficiency of radiation use (RUE, g MJ^{-1}) was computed at the grain yield and biomass levels (Li et al. 2022):

$$RUE_{TDM}\ (g\ MJ^{-1}) = \frac{TDM\ (g\ m^{-2})}{PAR_{abs}\ (MJ\ m^{-2})} \quad (5)$$

$$RUE_{GY}\ (g\ MJ^{-1}) = \frac{GY\ (g\ m^{-2})}{PAR_{abs}\ (MJ\ m^{-2})} \quad (6)$$

where, TDM is the total dry matter and GY is the grain yield.

2.7 Statistical Analysis

One-way analysis of variance (ANOVA), following Shapiro-Wilk's test for normality with the IBM SPSS 20.0 statistical package, was used to evaluate the impacts of varying levels of deficit irrigation on GY, LAI, $PAR_{abs,}$ and RUE. Multiple comparisons across the different irrigation treatments were performed using the Tukey test, with a significance level set at $P < 0.05$.

3. Results and Discussion

3.1 Leaf Area Index (LAI)

Results of LAI for three consecutive growing seasons of winter wheat are shown through Table 1. From those outcomes we observed that irrigation treatments had variable influences on the mean of LAI. The D1 treatments recorded the maximum values of LAI (4.30, 4.09, and 4.21), after that the FI treatments registered (4.23, 4.16, and 4.18), and the D2 treatments (3.86, 3.68, and 4.04) at (137, 135, and 135 DAS) in three seasons of (2021-2022, 2022-2023, and 2023-2024), respectively. Water stress on deficit water regimes of 75% ETc and 60% ETc (D1 and D2) was decreased as a result of rainfall substantial impact on increasing water content in all deficit irrigation water treatments.

The present findings align with Li et al. (2004). The reduction in LAI values was affected by the water deficit regime compared with the fully irrigated treatment. Additionally, Mubeen et al. (2013) observed that increased irrigation resulted in increased leaf area and other leaf properties. At the anthesis phase (heading stage), the LAI values of different treatments reached their maximum and decreased at the end of the season. Similarly, a strong relationship between water stress and LAI was reported by Longnecker (1994), and Nezhad Ahmadi et al. (2013). As leaf size influences leaf area and is negatively impacted by water stress deficiency, the negative effects of drought on wheat resulted in a significant drop in crop yield and morphological traits.

Table 1. Leaf Area Index (LAI) for three cropping seasons (2021-2024)

Seasons	**DAS**								
2021-2022	**38**	**88**	**104**	**118**	**137**	**150**	**164**	**175**	**196**
FI	0.48a	1.7la	2.86ab	3.83a	4.23a	2.86a	1.93a	1.06a	0.23ab
D1	0.56a	1.7la	3.03a	3.83a	4.30a	2.83a	1.86ab	1.06a	0.26ab
D2	0.46a	1.69a	2.88ab	3.80a	3.86b	2.37b	1.80ab	1.02a	0.34a
D3	0.48a	1.68a	2.65b	3.28a	3.77b	2.31b	1.72a	0.89a	0.20a
LSD (5%)	0.0338	0.0204	0.0913*	0.2195	0.0664*	0.0913*	0.0585*	0.0728	0.0392*
Seasons	**DAS**								
2022-2023	**35**	**89**	**105**	**119**	**135**	**155**	**165**	**179**	**-**
FI	0.51a	1.65a	2.89a	3.80a	4.11a	2.86a	1.88a	1.06a	-
D1	0.69a	1.95a	2.89a	3.88a	4.09a	2.95a	1.95a	0.69a	-
D2	0.64a	2.05a	2.97a	3.59a	3.68a	2.25ab	1.65ab	0.80a	-
D3	0.61a	2.12a	2.54a	2.64b	2.59b	1.70b	1.14b	0.40a	-
LSD (5%)	0.055	0.248	0.220	0.242*	0.218*	0.227*	0.163*	0.251	-
Seasons	**DAS**								
2023-2024	**35**	**80**	**105**	**115**	**135**	**150**	**165**	**175**	**197**
FI	0.47a	1.45a	2.76a	3.67a	4.18a	2.86a	2.01a	1.11a	0.33a
D1	0.61a	1.49a	2.75a	3.72a	4.21a	2.69a	1.92ab	1.04a	0.33a
D2	0.57a	1.53a	2.74a	3.62a	4.04a	2.33a	1.83ab	0.80ab	0.33a
D3	0.62a	1.45a	2.71a	3.38a	3.08b	1.55b	1.00b	0.48b	0.28b
LSD (5%)	0.0857	0.1357	0.1572	0.1265	0.2320*	0.1905*	0.2959*	0.1089*	0.0438

Note. DAS: Days after sowing; LSD: Least Significant Difference (5%).

3.2 Photosynthetically Active Radiation Absorbed (PARabs)

Table 2 illustrates the effect of irrigation treatments (FI, D1, D2, and D3) on the total PARabs at harvest for the three field experiments (2021-2024). It was observed that as irrigation doses increased, so did the total (cumulative) photosynthetically active radiation absorbed (PARabs). Actually, the FI and DI1 treatments had the highest PAR abs values (from 876.1 to 1126 MJ m^{-2}), followed by DI2 (from 841.3 to 1087 MJ m^{-2}). In contrast, the lowest value (from 738.8 to 1053 MJ m^{-2}) was recorded under D3 treatment. ANOVA analysis showed the accumulated PARabs in the three growing seasons (2021-2024) did not significantly differ between the DI and FI treatments ($P > 0.05$). Nevertheless, the total PARabs in D2, in contrast to FI, the cumulative PARabs in the D2 and D3 treatments were reduced by 1.7% and 4.9%, respectively. The PARabs in the D2 and D3 treatments dropped by 4 to 4.9 % and 8.8 to 15.7 %, respectively, for the second season (2022-2023) and the third season (2023-2024), in comparison to FI.

Table 2. The photosynthetically active radiation (PAR) absorbed for the three cropping seasons (2021-2024)

Season	**DAS**								
2021-2022	**38**	**88**	**104**	**118**	**137**	**150**	**164**	**175**	**196**
FI	4.44 b	182.5 a	295.7 b	411.2 ab	606.1 ab	761.4 a	911.1 a	1007.7 a	1106.6 a
D1	4.90 a	186.4 a	300.4 a	416.2 a	611.5 a	766.4 a	915.4 a	1012.2 a	1118.4 a
D2	4.50 b	182.5 a	295.4 b	410.8 ab	603.7 ab	752.4 a	894.1 b	986.5 b	1087.0 ab
D3	4.50 b	182.5 a	293.2 b	404.4 b	593.4 b	740.4 a	878.5 c	966.4 c	1053.0 b
LSD (5%)	0.085	2.01	1.13	2.45*	4.73*	9.09	4.07*	5.48*	15.09*
Season	**DAS**								
2022-2023	**35**	**89**	**105**	**119**	**135**	**155**	**165**	**179**	**-**
FI	3.10 b	201.8 a	322.9 a	458.2 a	640.8 ab	885.6 ab	1000.5 a	1126.2 a	-
D1	3.46 a	203.7 a	323.4 a	457.6 a	650.4 a	892.5 a	1004.6 a	1118.6 a	-
D2	2.80 c	201.4 a	322.4 a	455.1 a	631.5 ab	859.6 ab	961.9 b	1070.7 b	-
D3	2.71 c	199.7 a	315.5 a	435.9 a	592.1 b	790.4 b	872.7 c	948.1 c	-
LSD (5%)	0.253	12.84	9.29	29.03	17.24*	31.56*	10.11*	9.41*	-
Season	**DAS**								
2023-2024	**35**	**80**	**105**	**115**	**135**	**150**	**165**	**175**	**197**
FI	1.71 a	70.6 a	181.3 a	249.9 a	422.8 a	570.0 a	710.9 a	787.0 a	876.1 a
D1	1.79 a	72.0 a	183.3 a	251.7 a	424.6 a	570.2 a	707.8 a	782.3 a	876.6 a
D2	1.80 a	71.2 a	180.2 a	247.8 a	418.3 a	558.6 a	689.3 a	758.1 ab	841.3 a
D3	1.81 a	71.2 a	180.2 a	247.1 a	409.7 a	533.2 b	632.8 b	678.3 b	738.8 b
LSD (5%)	0.364	11.11	20.75	15.0	16.56	14.48	16.90*	27.28*	45.77

Note. DAS: Days after sowing; LSD: Least Significant Difference (5%).

3.3 Relation Between Total Dry Matter (TDM) Accumulation and Photosynthetically Active Radiation Absorbed (PARabs)

The results presented in Figure 3 shows the relationship between cumulative PARabs and the winter wheat TDM production for the three consecutive experiments (2021-2024) conducted under the four distinct water regimes (FI, D1, D2, and D3). RUE exhibits a high degree of variability based on the years (seasons) and irrigation water treatments. The highest RUE, which ranged from 1.35 to 1.48 g MJ^{-1} under treatment FI, was followed by DI1, which ranged from 1.27 to 1.42 g MJ^{-1}. The RUE for DI2 ranged from 1.21 to 1.32 g MJ^{-1}. The DI3 lowest RUE values ranged from 1.04 to 1.17 g MJ^{-1}. It is evident that, in comparison to FI, treatment DI3 reduced RUE from 21 to 23% and from 10.4 to 10.8% in treatment DI2 compared to FI.

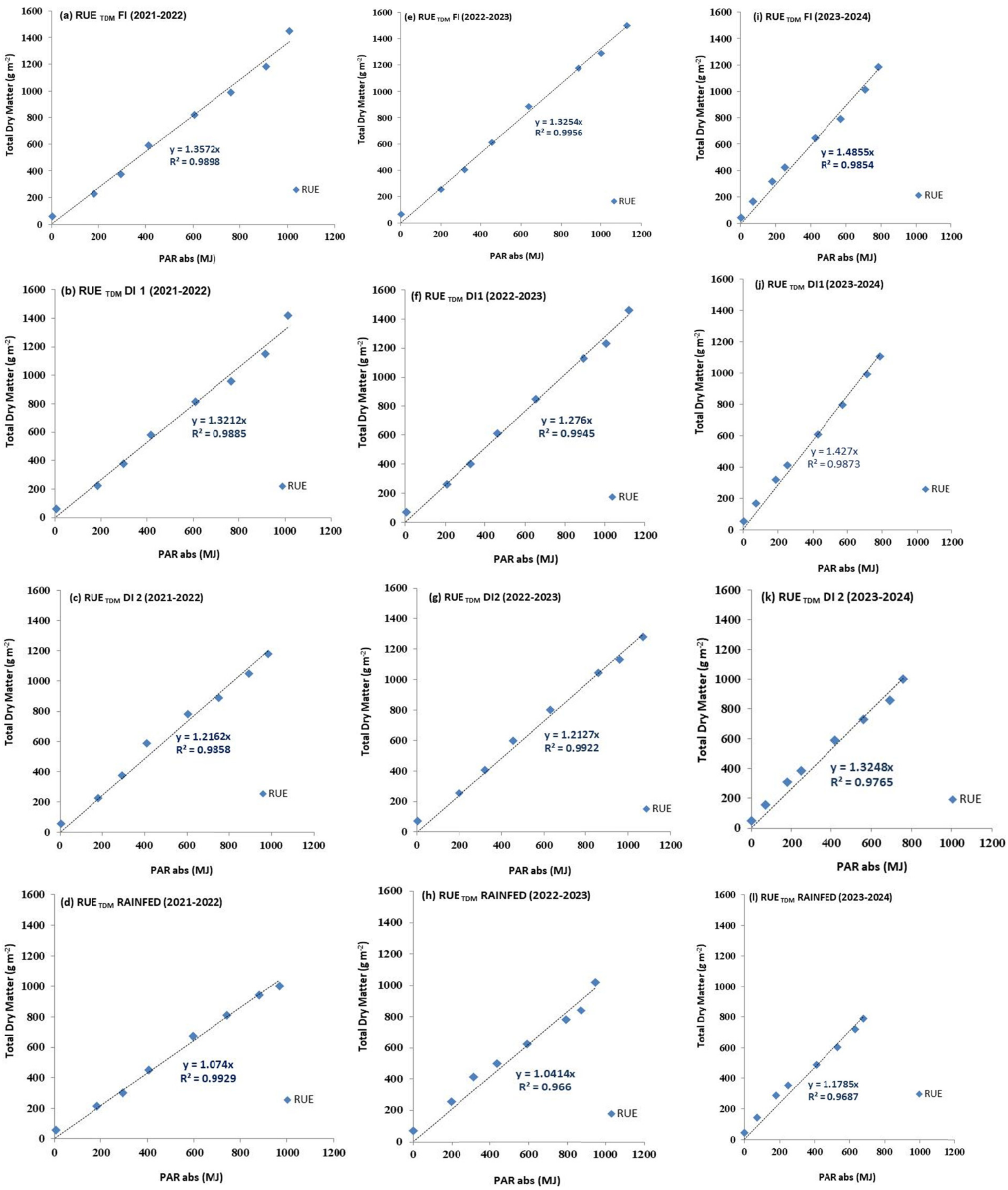


Figure 3. The relation between the cumulative PAR_{abs} and TDM in three cropping seasons (2021-2024)

3.4 Grain Yield and RUE_{GY}

The impact of various irrigation levels on PAR abs, Grain Yield (GY), and RUE_Y at wheat harvest for three experiments (2021-2024) is presented in Table 3. Findings revealed that the irrigation regime remarkably affects wheat yield; FI treatment recorded the highest amount of crop yield: 789.4, 759.7, and 665.1 g m^{-2} in the three growing seasons (2021-2024), respectively, followed by D1 with values of 745.2, 738.7, and 635.1 g m^{-2}. The lowest GY was registered under a rainfed treatment, and it decreased from 64.5 to 68.6% in the three experiments compared to FI. The results of ANOVA analysis showed that the treatments differed significantly ($P < 0.05$), during the second cropping season (2022-2023) variance analysis revealed no significant impact ($P \geq 0.05$)

between FI and DI. The RUEY in all FI treatments and in the three experiments has registered the highest levels of 0.71, 0.68, and 0.76, respectively. It was observed that there was a reduction in RUEY of D1 and D2 in the first season by 6.6% and 51.9%, respectively, compared with FI. Under the D2 at the second and third seasons, the RUE Y values decreased from 28.6 to 43% compared to the control treatment.

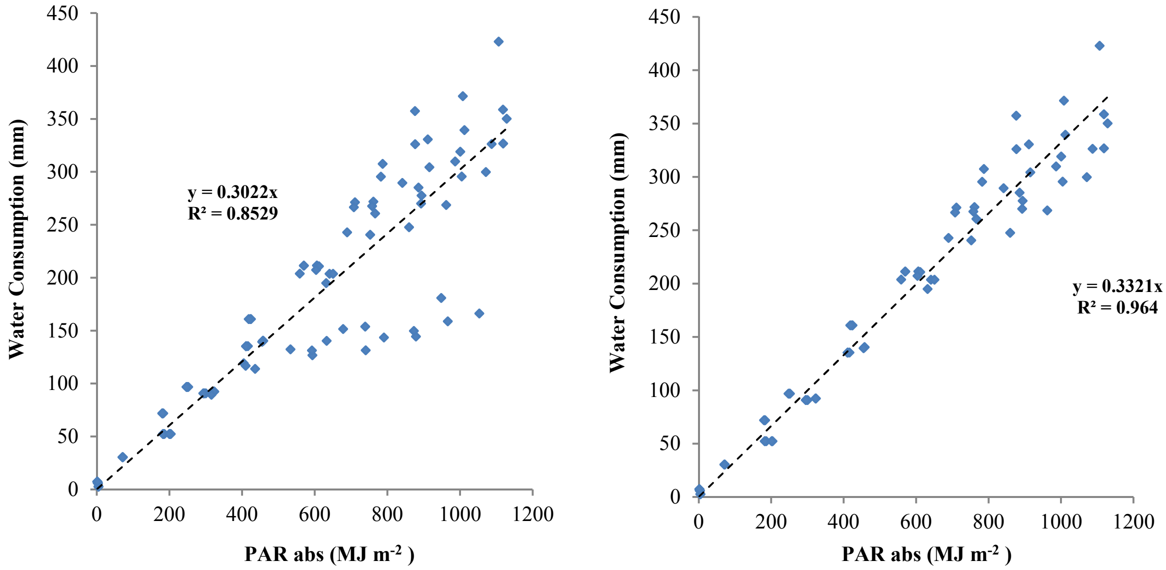
Table 3. Photosynthetically active radiation absorbed (PARabs), Grain Yield (GY) and Radiation use efficiency for Grain yield (RUE_Y) at harvest for three cropping seasons (2021-2024).

	PAR abs (Mj m^{-2})	**Grain Yield (g m^{-2})**	**RUE_Y**
2021-2022			
FI	1106.6 a	789,4 a	0.71a
D1	1118.4 a	745,2 b	0.67b
D2	1087.0 ab	373 c	0.34c
D3	1053.0 b	258,9 d	0.24d
LSD (5%)	15.09*	8.245*	0.03*
2022-2023			
FI	1126.2 a	759.7 a	0.68a
D1	1118.6 a	738.7 a	0.66a
D2	1070.7 b	412.2 b	0.38b
D3	948.1 c	269.8 c	0.28c
LSD (5%)	9.41*	10.98*	0.015*
2023-2024			
FI	876.1 a	665.1a	0.76a
D1	876.6 a	635.1b	0.72a
D2	841.3 a	455.8c	0.54b
D3	738.8 b	208.6d	0.282c
LSD (5%)	45.77*	9,7*	0,037*

Note. RUE_Y: Radiation use efficiency for Grain yield; LSD: Least Significant Difference (5%).

3.5 Relation of Photosynthetically Active Radiations Absorbed and Water Consumption.

Figure 4 shows the correlation between water consumption and photosynthetically active radiation absorbed during three consecutive cropping seasons (2021-2024) under four treatments (FI, D1, D2, and D3). Total (cumulative) crop water consumption increased linearly with total (cumulative) PAR abs values for the two treatments (FI and D1) over the course of the three seasons. The findings demonstrated that the water deficit treatment helps reduce crop water use, which improves WUE and affects PARabs in the severe water treatments of rainfed. The slopes of these curves of FI, D1, and D2 (Figure 4a) and FI, D1, D2, and D3 (Figure 4b) have varied from 0.3321 to 0.3022. The relationship between accumulated WC and PAR during phonological stages was deviated as it is shown in Figure 4b.



(a) (b)

Figure 4. The relation of photosynthetically active radiation absorbed and crop water consumption with four irrigation treatments (FI, D1, D2 and D3) in three consecutive cropping seasons (2021-2024)

4. Discussion

Through the three consecutive cropping seasons of applying different rates of irrigation (FI, D1, D2, and D3) at harvest, the following variables were examined: photosynthetically active radiation absorbed (PARabs); radiation use efficiencies for TDM (RUE_{TDM}); RUE for grain yield (RUE_Y); and the relationship between photosynthetically active radiation absorbed and water consumption. As results all irrigation regimes in three cropping seasons have a variable effect on the LAI. The D1 and FI treatments recorded maximum values of LAI. In the D1 treatment, the LAI varied from 4.1 to 4.3, followed by FI (from 4.1 to 4.2). But, in the D2 treatment, the LAI ranged from 3.7 to 4. Conversely, in the D3 treatment and at all cycles, the LAI registered the lowest values and decreased by 13.1 to 62.3%. ANOVA variance analysis data shows no significant effect ($P \geq 0.05$) in the second and third seasons between FI, D1, D2, and D3 till 105 and 115 DAS, respectively, while there was a significant effect ($P < 0.05$) between FI, D1, D2, and D3 in 119 DAS. This can be attributed to the significant effect of rainfall water to enhance soil water content under all levels of deficit irrigation, which reduced the water stress on deficit water regimes of 0.75 ETc and 0.60 ETc (D1 and D2). The present findings align with Li et al. (2004). The reduction in LAI values was affected by the water deficit regime compared with the fully irrigated treatment. A strong relationship between water stress and LAI was reported by Longnecker (1994), and Nezhad Ahmadi et al. (2013). As can be observed, the effect of incident photosynthetically active radiation was found to be strongly correlated with the LAI across all applied water rates. This is because water stress reduced the LAI, which in turn reduced the interception of photosynthetically active radiation and RUE (O'Connell et al., 2004). According to De Wit (1965), the rate at which well-watered leaves perform photosynthesis directly limits RUE in the canopy.

A difference in the response of TDM to cumulative PARabs was noticed in all irrigation rates of the three consecutive cropping seasons. Similarly, we detected a strong linear relationship between PARabs and TDM throughout different growth stages (emergence, tilling, stem elongation, heading, dough stage, and maturity), showing an increase in TDM production as the crop developed. This suggests that the use of PARabs is more efficient when the irrigation water meets the crop requirements. The response to different factors that affect respiration and photosynthesis rates during a particular growing period or throughout the entire growth stages is reflected in RUE (Gou et al., 2017; Gifford et al., 1984; Andrade et al., 1993). Water shortage also reduces RUE, particularly during grain filling. Our findings demonstrated a significant decrease in the TDM production as water stress increased. In the D2 treatment, the TDM production declined by 30.3% to FI. One possible explantation for this could be to the depletion the in soil water under the thresholds of RAM at the root zone system during the post-anthesis phase. These outcomes concur with those reported by Acevedo et al. (2002) and Katerji et al. (2008). Consequently, it influenced LAI by reducing the leaf size. Therefore, photosynthesis is the primary source of TDM and grain yield of crop plants. Shao et al. (2005), whenever impacting LAI negatively, could result in TDM reduction. Water stress can lower RUE by decreasing the photosynthetic rate of leaves, according to Uhart and Andrade (1995). In the D3 treatment and at the first physiological stages (emergence, tillering, jointing), results showed that TDM accumulation increased gradually (from 58.6 g m^{-2} to 1050.8 g m^{-2}) with increased PAR abs (from 4.5 to 1053 MJ m^{-2}) in 196 DAS. In comparing D3 with FI, the TDM had reduced by 40%. This may have been explained as the water stress began to be notable at post-anthesis (heading, dough stage, and maturity), as soil water depleted at the thresholds of RAM and interacted with the wilting point; this corroborates the findings of Akram (2011). In the second season (2022-2023), we observed that the TDM, PARabs, and RUE were influenced by irrigation water doses of FI, D1, D2, and D3; results showed an increase in the amount of TDM, PARabs, and RUE in all irrigation treatments before declining to a minimum during the post-anthesis while the water stress was excessed by deficit treatments. Our results present variability in TDM and PAR abs in the irrigation regime of (D1, D2, and D3) compared with FI treatment when the decline in TDM was found to be 2.8%, 14.8%, and 32%, and the decrease in PARabs was 1%, 5%, and 15.8%, respectively. Meanwhile, the D3 treatment depended on the uneven events of rainfall the crop imposed to sever water stress during the growth cycle as transpiration and photosynthesis rates were affected at the anthesis and grain-filling stages; moreover, the soil moisture in the root zone system area had depleted extensively at the post-anthesis phase. Therefore, a deviation in RUE occurred, resulting in a remarkable reduction in TDPM. It is a fact that fully irrigated treatment creates convenient conditions in the root zone system area for crop TDM, which is in conformity to the results of Tahmasabi et al. (2000). For the third season (2023-2024), the results showed an increase in cumulative TDM in the treatment D1 by 5.8% compared to FI. The D2 had a reduction of 19.7% and 4%, while the D3 treatment recorded 40% and 15.7% less than the control treatment in TDM production and cumulative PARabs, respectively. As the results indicated a deviation in RUE while the crop was imposed to a water stress regime throughout growth stages, the physiological traits such as transpiration, photosynthesis, leaf gas exchange, and TDM production were being affected, especially during the pre-flowering stage. This is consistent with the findings of Pankovic et al. (1999), and Ripley et al. (2007), who found a relationship between the degree of water stress and the stomatal closure magnitude and the decline in the leaf transpiration mechanism. According to Luo et al. (2011), and Gan et al. (2013), crop leaf senescence and water stress levels cause a significant decrease in biomass translocation before and after flowering. Water scarcity can limit canopy expansion or predict leaf senescence by reducing the interception of incident solar radiation through leaf rolling or severe wilting (Guo et al., 1998; Ngugi et al., 2013). Since the rainfed represents the severe water stress, the soil water content in the root zone system area remains decreased below the field capacity and fluctuates between RAM and PWP thresholds as long as the crop experiences uneven precipitation events during the season.

4.1 Grain Yield and RUE_Y at Harvest

Table 3 shows the Grain Yield and RUE_Y at the harvest phase for the three consecutive experiments (2021-2024). Grain yield was greatly influenced by the irrigation dosage. For each of the three growing seasons, a high value was noted under FI dose (789.4, 759.7, and 665.1 g m^{-2}). For rainfed regime D3, the grain yield dropped to 258.9, 269.8, and 208.6 g m^{-2}, respectively. These results concurred with those of Ahmad et al. (2022), and Sallam et al. (2019). According to Zeng et al. (2023), grain yield is decreased by severe water deficiency before flowering. In addition, dehydration brought on by severe water resulted in the release of ROS (reactive oxygen species) and a decrease in crop biomass, both of which decreased wheat yield (Keyvan 2010). Water stress primarily occurred during the entire post-anthesis phase in the current study, affecting all irrigation treatments that were used. This would account for the decrease in crop yield. The number of grains set per unit of biomass at the anthesis phase seemed to be positively correlated with RUE at post-anthesis, according to Miralles and Slafer (1997), who observed that FI allowed RUE to stay comparatively constant throughout the crop cycle. The RUE-GY values vary because there was clear evidence of a decrease in winter wheat yield as water stress levels rose, with the largest decrement occurring at the highest water deficit levels. Clear evidence of winter wheat yield reduction was observed when water stress levels increased, with the most significant decrement occurring at the highest water deficit levels; thus, the RUE_Y values vary from FI to D3 regimes. Statistical analysis showed a significant effect ($P < 0.05$) between treatments of the experiments. Crop yield is a result of various metabolic reactions, with variables affecting the production process that might influence the final product (Ghanem et al., 2024).

4.2 Photosynthetically Active Radiation—Water Consumption Relationship

Figures 3a and 3b exhibited a regression relationship of a consistent trend over a wide range of PARabs and crop water consumption under different irrigation regimes in three consecutive cropping seasons (2021-2024). We found that the amount of crop water used was closely correlated with the amount of photosynthetically active radiation absorbed, or PARabs. The results showed linearly increasing in different crop growth stages of FI, CD1, and CD2 irrigation treatments. Similar results on sweet potato and winter wheat under various nitrogen applications were reported by Rezig et al. (2007, 2010, 2015). They reported a significant linear relationship between CWC and PARabs accumulated. This relationship is influenced by water availability in the root zone system when moisture content frequently depletes to RAM thresholds while the irrigation and rainfall events were refilling root zone depth of soil to the available water content under water deficit treatments of D1 and D2. The impact of (D3) in three experiments was given in Figure 2b as the deficit irrigation of rainfed had significant effects on water consumption. The relationship was curvilinear during the post-anthesis phase as the crop had been exposed to water stress. The results show WC was affected negatively by deficit irrigation and declined to a minimum when the crop root zone was at the permanent wilting point until the harvesting phase. The slopes of the curves and the regression coefficients R2 for the treatments of (FI, D1, and D2) and (FI, D1, D2, and D3) were (RUE 0.3321, 0.3022, and $R^2 = 0.989$, 0.953), respectively. According to Sun et al. (2024), the disparities in the correlations were ascribed to changes in climatic factors, crop varieties, and irrigation water deficit during the course of the cropping season. The cumulative PARabs was observed to be increased in all irrigation water treatments throughout the growing cycle of the three cropping seasons. The highest values of the cumulative PARabs were 1118.4, 1126, and 876.6 MJ m^{-2}, respectively. D3 treatment recorded the lowest value in three seasons: 1053, 948.1, and 738.8 MJ m^{-2}, respectively. The findings approved that the water stress can reduce crop water consumption, which could enhance WUE and impact PARabs in the severe water treatments of rainfed; the relationship between accumulated WC and PAR during phonological stages was deviated in the period (March-June) during the anthesis phase and grain filling stages since WC was gradually reduced cumulatively until harvest. The ability to convert intercepted radiation into crop water requirements is a benefit of using this relation to calculate PARabs (Rezig et al., 2015).

5. Conclusion

Our results showed that deficit irrigation doses significantly affected PARabs of the durum wheat. RUE was significantly positively correlated with CWC and PAR utilization. Nonetheless, significant variations were noted in the amount of PAR that was intercepted by the crop across various water treatments. Furthermore, a cost-effective, precise smart soil-water sensor (tensiometer) was utilized to estimate crop water requirements and crop water consumption in real time to set up an irrigation schedule under deficit irrigation regimes. Additionally, the relationship between photosynthetically active radiation (PAR abs) and crop water consumption (CWC) showed a strong correlation between the two parameters, making it possible to estimate the crop water requirements of large-scale planted crops (cereal crops).

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Authors Contributions

Conceptualization, M.R. and H.D.; methodology, M.R. and H.D.; software—IoT and smart tensiometer, WaziSence, WaziGate, and WaziCloud, M.A.R., C.D. and F.M.; validation, M.A.R., C.D. and M.R.; formal analysis, S.B and B.L.; investigation, M.R and H.D.; data curation, M.R., M.A.R., C.D. and F.M.; writing—original draft preparation, S.B., W.B., M.R., M.A.B.A. and H.D.; writing—review and editing., M.R. and H.D.; supervision, M.R. and H.D.; project administration, M.R. and M.A.R. All authors have read and agreed to the published version of the manuscript.

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