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Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California

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Doctorado en Ciencias
en Ciencias de la Vida
con Orientación en Biología Ambiental

Precision agriculture and irrigation strategies to improve crop water productivity of chickpeas (Cicer arietinum L.)

Tesis
para cubrir parcialmente los requisitos necesarios para obtener el grado de
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Presenta:

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Resumen de la tesis que presenta **José Denis Osuna Amador** como requisito parcial para la obtención del grado de Doctor en Ciencias en Ciencias de la Vida con orientación en Biología Ambiental.

Agricultura de precisión y estrategias de irrigación para mejorar la productividad del agua en garbanzos (Cicer arietinum L.)

Resumen aprobado por:

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La demanda de agua para satisfacer la producción de alimentos de una población creciente y la escasez de éste recurso implica la evaluación y aplicación de estrategias que incrementen la productividad del agua en cultivos (CWP, del inglés crop water productivity). Por lo anterior, el objetivo de este trabajo fue evaluar la modulación del rendimiento de grano (GY) y la CWP de cultivos de garbanzos establecidos en riego por goteo bajo diferentes estrategias de irrigación deficitaria, a la vez de utilizar sensores remotos montados en drones para determinar la respuesta del cultivo a diferentes esquemas de irrigación. Establecí en 2020 y 2021 dos experimentos en bloques completos al azar con cuatro replicas para evaluar estrategias de irrigación deficitaria regulada (RDI) y sostenida (SDI) y sus efectos en variables productivas en el cultivo. Los tratamientos de RDI variaron el nivel de restricción del riego por etapa fenológica considerando la aplicación del 50 y 75 % de la evapotranspiración del cultivo (ETc), mientras que SDI consideró la aplicación del 75 % ETc durante las etapas del cultivo; el marco de siembra utilizado en estas dos parcelas fue camas con doble hilera de planta y los volúmenes de irrigación total de tratamientos variaron entre 897.84 y 1497.54 m^3 ha^{-1}. En el año 2022, se estableció una tercera parcela experimental en bloques completos al azar con cuatro replicas en el que se evaluaron las estrategias RDI (75 % ETc en etapa vegetativa), SDI (75 % ETc desde crecimiento vegetativo ha llenado de cápsula), además de la irrigación con secado parcial de zona radicular (PDI) aplicado el 75 % de ETc en etapa vegetativa, floración y llenado de cápsula; los tratamientos de RDI y SDI se establecieron en sistema de camas con doble hilera de planta y los de RDI en sistemas de hilera sencilla con un rango de irrigación total entre 2224.66 a 3438.81 m^3 ha^{-1}. Los resultados de los experimentos 2020 y 2021 mostraron la relevancia de aplicar el 100 % ETc durante la etapa de floración y que aplicar el RDI empleando el 75 % ETc es una alternativa para incrementar la productividad del agua; GY y CWP en este tratamiento alcanzaron 1124.8 kg ha^{-1} y 0.95 kg m^{-3}, respectivamente, y ahorró 24 m^3 ha^{-1}. En 2022, los tratamientos sobresalientes en GY y CWP fueron aquellos que implementaron PDI e irrigación completa establecido en hilera sencilla; lograron un rango de GY entre 1430.0 y 1552.5 kg ha^{-1} y CWP de 0.53 a 0.6 kg de grano m^{-3}; el ahorro de agua varió de 85 a 396 m^3 ha^{-1}. Este experimento, denotó que el NDVI y CTD pueden predecir GY y CWP, y que la determinación de estas características al final de la etapa de floración resultó en modelos de mayor confianza. La investigación mostró el beneficio de utilizar el PDI en floración como estrategia sobresaliente en el ahorro de agua, incremento de CWP, sin afectar el GY en garbanzos producidos en riego por goteo.

Palabras clave: Estrategias de irrigación, rendimiento de grano, VANTs, IR térmico y multiespectral, índices de vegetación, temperatura del dosel.

Abstract of the thesis presented by **José Denis Osuna Amador** as a partial requirement to obtain the Doctor of Science degree in Life Sciences with orientation in Environmental Biology

Precision agriculture and irrigation strategies to improve crop water productivity of chickpeas (Cicer arietinum L.)

Abstract approved by:

Dr. Rodrigo Méndez Alonzo	**Dr. Armando Trasviña Castro**
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The water demand to achieve the food production for a growing population and the scarcity of this resource, implies evaluating different strategies to increase crop water productivity (CWP). I evaluated how different deficit irrigation strategies modulate grain yield (GY) and CWP in chickpeas established under drip irrigation, and simultaneously, I associated the crop's response to different irrigation schemes with multispectral and thermal imagery obtained from remote sensors mounted on drones. Two randomized complete block designs with four replicates were established in 2020 and 2021 to evaluate the response of seven productive variables in regulated deficit irrigation (RDI) and sustained deficit irrigation (SDI) strategies. The RDI treatments varied the level of irrigation restriction by phenological stage, considering the application of 50 and 75 % of the crop evapotranspiration (ETc), while SDI considered the application of 75 % ETc during the crop stages; the plant spatial arrangement utilized in these two experimental plots was beds-system with a double row of plants and treatments' total irrigation varied between 897.84 and 1497.54 m^3 ha^{-1}. In 2022, a third experimental plot was established in a complete randomized block design with four replicates in which the RDI (75 % ETc in vegetative stage), SDI (75 % ETc from vegetative growth to pod-filling) strategies, and partial root-zone drying irrigation (PDI) applied 75 % of ETc in the vegetative stage, flowering, and pod-filling; RDI and SDI treatments were established in bed-systems with double row of plant while PDI considered single-row of plant and total irrigation varied between 2224.66 and 3438.81 m^3 ha^{-1}. My results showed the relevance of applying 100 % ETc during the flowering stage and that applying RDI using 75 % ETc during vegetative growth is an alternative to increase water productivity; GY and CWP in this treatment reached 1124.8 kg ha^{-1} and 0.95 kg of grain m^{-3}, respectively, and saved 24 m^3 ha^{-1}. In 2022, the standout treatments in GY and CWP were those that implemented PDI and full irrigation in a single-row system; these achieved a GY range of 1430.0 and 1552.5 kg ha^{-1} and CWP of 0.53 to 0.6 kg of grain m^{-3}; water savings ranged from 85 to 396 m^3 ha^{-1}. This experiment showed that NDVI and CTD could predict GY and CWP, and that determining these characteristics at the end of the flowering stage resulted in higher confidence models. My research shows the benefit of using PDI in flowering as an outstanding water-saving strategy, increasing CWP without affecting the GY in chickpeas produced in drip irrigation.

Keywords: Irrigation strategies, grain yield, drone, remote sensing, NDVI, Canopy Temperature Depression.

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Glossary

Key	Description	Unit
ANOVA	Analysis of variance	-
AVERAGE	Method as the grouping criteria in SAS	-
$B_{(i)k}$	Effect of the block within the $_i$th year,	
Bed-system	Seedling system that employee drip tape separated by 1.6 m with double row of plants	-
B_j	Effect of the block	
BY	Biological yield	kg m^{-2}
Cal	Grain caliber	Number of grain in 30 g sample
cm^2	Square centimeter	-
CT	Canopy temperature	°C
CTD	Canopy temperature depression	°C
CWP	Crop water productivity	kg m^{-3}
dS m^{-1}	decisiemens per meter	-
$E_{(i)jk}$	Experimental error in serie of experiment (two year) in complete randomized block design	
Eij	Experimental error in complete randomized block design	
ETc	Crop evapotranspiration	mm
ETo	Reference evapotranspiration	mm
F	Flowering stage	-

F_{50}	Regulated deficit irrigation applying 50 % of ETc during flowering stage	-
F_{75}	Regulated deficit irrigation applying 75 % of ETc during flowering stage	-
FI	Full irrigation treatments (100% ETc)	-
FI-B	Full irrigation + bed-system with a double row of plants	-
FI-S	Full irrigation + plants in single-row	-
FLIR	Forward looking infrared	-
g	Gram(s)	-
G	Green band 550 wavelength, 40 nm bandwidth	-
GDD	Growing degree days	-
GP	Grains per plant	Number of grains
GY	Grain yield	kg ha^{-1}
H	Plant height	m
HI	Harvest index	-
i.e.	Id est, which is Latin for “that is”.	-
INIFAP	Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias	-
IPCC	Intergovernmental Panel on Climate Change	-
ISPA	International Society of Precision Agriculture	-
IWR	Irrigation water requirement	mm
K	Potassium	mg kg^{-1}

Kc	Crop coefficient	-
kWh	Kilowatt hour	-
LSD	Least significance difference	-
m^3	Cubic meter	-
mg kg^{-1}	Miligrams per kilogram	-
NDVI	Nomalized difference vegetation index	-
NIR	Near-infrared band 790 nm wavelength, 40 nm bandwidth	-
nm	Nanometer	-
NO_3	Nitrate	mg kg^{-1}
OI-B	Over irrigation applied during VG, F, and PF stages + bed-system with a double-row of plants.	-
P	Precipitation	mm
p	Probability (level of significance)	-
P_2O_5	Phosphorus pentoxide	mg kg^{-1}
PC1	Principal component number one	-
PC2	Principal component number two	-
PC3	Principal component number three	-
PCA	Principal component analysis	-
PDI	Partial root-zone drying irrigation	-
PDI_F-S	Partial root-zone drying irrigation applied during F stage + plants in single-row	-

PDI_{PF}-S	Partial root-zone drying irrigation applied during PF stage + plants in single-row	-
PDI_{VG}-S	Partial root-zone drying irrigation applied during VG stage + plants in single-row	-
PDW	Plant dry weight	g $plant^{-1}$
Pe	Effective precipitation	mm
PF	Pod-filling stage	
PF_{50}	Regulated deficit irrigation applying 50 % of ETc during pod-filling stage	-
PF_{75}	Regulated deficit irrigation applying 75 % of ETc during pod-filling stage	-
pH	Potential of hydrogen	-
PP	Pods per plant	Number of pods
PROC CLUSTER	Cluster procedure developed in SAS software	-
r	Pearson correlation coefficient	-
R	Red band 660 nm wavelength, 40 nm bandwidth	-
R^2	Coefficient of determination	-
RDI	Regulated deficit irrigation	-
RDI_{VG}-B	Regulated deficit irrigation applied in VG stage + bed-system with a double row of plants	-
RE	Red edge band 735 nm wavelength, 10 nm bandwidth	-
RGB	Red-green-blue	-

RHmax	Maximum relative humidity	%
RHmean	Mean of relative humidity	%
RHmin	Minimum relative humidity	%
SAR	Sodium adsorption ratio	-
SAS	Statistical Analysis System	-
SDI	Sustained deficit irrigation	-
SDI_{75}	Sustained deficit irrigation applying 75 % of ETc during vegetative growth, flowering and pod-filling stages in chickpea	-
SDI-B	Sustained deficit irrigation + bed system with a double row of plants	-
SEMARNAT	Secretaría de Medio Ambiente y Recursos Naturales	-
Single-row	Seedling system that employee drip tape separated by 0.8 m with single-row of plants	-
SMN	Servicio Meteorológico Nacional (México)	-
T	Temperature	°C
Ti	Total irrigation for crop in a season	m^3 ha^{-1}
T_j	Effects of the $_j$th treatment	
Tmax	Maximum temperature	°C
Tmean	Average temperature	°C
Tmin	Minimum temperature	°C
UAV	Unmanned aerial vehicle	-

UAVs	Unmanned aerial vehicles	-
VG	Vegetative growth stage	-
VG_{50}	Regulated deficit irrigation applying 50 % of ETc during vegetative growth	-
VG_{75}	Regulated deficit irrigation applying 75 % of ETc during vegetative growth	-
Y_i	Effect of the $_i$th year	
Y_{ijk}	The response variable measured on the $_{ijk}$ experimental unit (plot)	
YT_{ij}	Interaction of the $_i$th level of Y with the $_j$th level of T_j	
µ	The overall mean	
µm	Micrometer	-
ρ_{NIR}	Reflectance in the spectral range of the near infrared	
ρ_R	the reflectance in the spectral range of red	
$	Mexican pesos	-
°C	Celsius degree	-
9N	Scheme of energy service cost (water for agricultural uses)	-

Chapter 1. Introduction

One of the principal challenges of modern agricultural science is to improve crop productivity through advances in knowledge and new technologies to achieve a more efficient use of available resources (Arús, 2020). Given a growing population, with limited freshwater resources, and increased competition to allocate water for domestic and industrial purposes, producing sufficient food by increasing crop productivity is one of the most critical challenges of this century (Soltani, 2016; Food and Agriculture Organization of the United Nations [FAO], 2017). This complex situation turns even more pressing for arid and semiarid regions of the world, which may have been already experiencing abnormal droughts (Woodhouse et al., 2010; Intergovernmental Panel on Climate Change [IPCC], 2023).

Agriculture uses 70% of the globally available freshwater and coupled with population growth and food demands, this implies a potential increase in agricultural production by 70% for the year 2050 (The World Bank, 2023). The high demand for freshwater for crop production shows how agriculture is both a cause and a victim of water scarcity.

The current situation of freshwater scarcity and resource utilization by agriculture generates the urgent need to increase crop water productivity; this is the crop yield ratio to the consumed water (Heydari, 2014; Letseku & Grové, 2022). Under this scenario, a farmer´s goal should be to optimize revenue per water unit rather than per land unit (Ferere & Soriano, 2007). For the scenario described, the consensus is that even though current systems can produce enough food, sustainable transformation is required (Vos & Bellù, 2019). In the same sense, we consider that implementing precision agriculture techniques or irrigation strategies like deficit irrigation can contribute to improving productivity and sustainability in crop production (Jovanovic & Stikic, 2018; Abdelkhalik et al., 2019; International Society of Precision Agriculture [ISPA], 2021).

Deficit irrigation deliberately manipulates irrigation to reduce water volumes below the plant´s optimal water requirements (Ferere & Soriano, 2007). Deficit irrigation is a valuable strategy to stimulate increases in crop water productivity without involving additional water, especially when the value of harvest is low and water cost is high. Deficit irrigation consists of different schemes, such as regulated irrigation (RDI), sustained deficit irrigation (SDI), or partial root-zone drying irrigation (PDI) (Elsheik et al., 2012; Chai et al., 2016; Singh et al., 2021; Yang et al., 2022). RDI is a widely known scheduling method that consists of the variable application of crop irrigation in specific stages of plant development, usually focusing on water volumes that are under or equal to the full requirement for optimal plant growth (Endalu & Temesgen, 2020). In contrast, SDI applies below-optimal water volumes during each irrigation event for the crop cycle (Chalmers, 2007). Finally, PDI is an irrigation technique that modifies the spatial location of irrigation: when one side of a plant's roots faces drought, simultaneously, the other side receives watering. Under this management, the irrigation rotates to generate wet/dry sides. The theoretical background of partial root-zone drying irrigation is that the wet side of the root keeps the plant canopy in favorable water conditions. In contrast, the drought in other parts of the roots produces root chemical signals, i.e., abscisic acid production (Jovanovic & Stickic, 2018).

Precision agriculture, on the other hand, is defined as "a management strategy that gathers, processes, and analyzes temporal, spatial, and individual data and, combined with physiological information, supports management decisions taking into account estimated variability to improve the efficiency of resources, productivity, quality, profitability, and sustainability of production" (ISPA, 2021); this is an essential approach to increase crop water productivity (Zeng et al., 2021). In precision agriculture, the use of remote sensing technology has rapidly increased during the past few decades because of the unprecedented availability of high-resolution satellite imagery. Most recently, remote sensing from unmanned aerial vehicles (UAVs) provides optical, multispectral, and infrared imagery for use in many precision agriculture applications, including crop monitoring, irrigation management, nutrient application, disease and pest management, and grain yield prediction (Sishodia et al., 2020; Velusamy et al., 2022).

Remote sensing from a multispectral or infrared camera mounted on a UAV allows for studying vegetation conditions. Multispectral images enable vegetation index calculation, while infrared images allows to monitor the plant´s canopy temperature. UAV monitoring has gained importance because there is no satellite, at least with free access, which can monitor the daily temporal frequency and with enough surface detail for farm-level analysis (Ihuoma & Madramootoo, 2017; Sagan et al., 2019; Filgueiras et al*.,* 2019).

Given the short life cycle of pulses, and also because of their importance for global food security, it is critical to quantify the relevance of the implementation of different deficit irrigation strategies (RDI, SDI, and PDI) and the application of precision agriculture (multispectral and infrared imagery) to increase crop water productivity. In conjunction, our results will provide a guide to establish and improve the referred technologies for chickpeas growing in the semiarid regions of the world. In particular, this work evaluated different deficit irrigation strategies and thermal and multispectral images obtained with UAVs, applied to irrigation monitoring and grain yield prediction in chickpea crops (*Cicer arietinum* L.).

1.1. Background

Successful applications of RDI, SDI, and PDI in pulses, such as common bean (*Phaseolus vulgaris* L.) (Simsek et al., 2011), pea (*Pisum sativum* L.) (Hirich et al., 2014), and faba bean (*Vicia faba* L.) (Eskandari & Kazemi, 2020) have led to enhanced crop water productivity. However, for chickpea (*Cicer arietinum* L.), the third most intensively established legume globally, few reports have tested the advantage of deficit irrigation implementation (Hirich et al., 2011; Hirich et al., 2014; Douh et al., 2021). Concerning precision agriculture techniques, several works on using multispectral (Srivastava et al., 2022; Avneri et al., 2023) and infrared images (Purushothaman et al., 2015; Pineda et al., 2020) for different crops have been published, but we could not find published work reporting the monitoring of chickpea under different deficit irrigation strategies.

1.2. Hypothesis

Deficit irrigation strategies allow the maximization of chickpea grain yield and increasing crop water productivity. At the same time, using UAV-mounted remote sensing can detect the crop's response to variant irrigation schemes, as well as predict grain yield and crop water productivity.

1.3. Objectives

1.3.1. General objective

To evaluate how the different deficit irrigation strategies on chickpea (*Cicer arietinum* L.) module grain yield and crop water productivity under drip tape conditions, and to predict by the use of UAV-mounted remote sensing the response of crop to several schemes of irrigation.

1.3.2. Specific objectives

- To evaluate the effects of regulated deficit irrigation (RDI) and sustained deficit irrigation (SDI) on chickpea production performance using different levels of irrigation restriction by growth stage under drip tape conditions and bed system (Chapter 2).

- To evaluate the effects of regulated deficit irrigation (RDI), sustained deficit irrigation (SDI), and partial root-zone drying irrigation (PDI) on chickpea production performance under drip irrigation conditions with spatial arrangement of plants in single-row and beds systems. In addition, to test the use of the Normalized Difference Vegetation Index and Plant Canopy Temperature Depression derived from UAV-mounted multispectral and infrared remote sensing to predict grain yield and water productivity (Chapter 3).

- Based on the information generated in the previous specific objectives, generate a cluster of treatments and their corresponding description that allows the identification of outstanding deficit irrigation strategies for grain yield and water productivity (Chapter 4).

Chapter 2. Regulated deficit irrigation during vegetative growth enhances crop water productivity in chickpea (*Cicer arietinum* L.)

2.1. Abstract

To optimize irrigation, agronomists need to modulate crop water productivity (CWP) throughout phenology. We compared regulated deficit irrigation (RDI) and sustained deficit irrigation (SDI) in chickpea (*Cicer arietinum* L. var. Blanoro), expecting RDI during vegetative growth (VG) to enhance CWP, as opposed to flowering (F) and pod-filling (PF) stages. The effects of RDI and SDI on grain yield, plant height, weight, grain caliber, pods and grains per plant, harvest index, and CWP, were tested through a complete randomized block experiment during the years 2020 and 2021, comparing full irrigation (FI, ETc = 100%), SDI (SDI_{75}, ETc = 75% during all stages), and six RDI treatments varying in ETc % across phenology: VG_{50}, VG_{75}, F_{50}, F_{75}, PF_{50}, and PF_{75}. VG_{75} had higher CWP while minimizing impacts on productivity. During 2020, the plants were taller (0.44 ± 4.4 m), and increased in harvest index (0.47 ± 0.06), and CWP (0.90 ± 0.2 kg m^{-3}) ($p < 0.05$), while in 2021, plants were heavier (11.4 ± 2.8 g) and increased in caliber (46.1 ± 3.0 grains); grain yield did not differ between years ($p > 0.05$), reaching 861.8 (2020) and 944.7 kg ha^{-1} (2021). Our results highlight the relevance of maintaining 100% ETc during flowering, and the maintenance of RDI at 75% ETc during vegetative growth.

2.2. Introduction

Owing to human-induced climatic changes, an increase in the recurrence and intensity of droughts in several areas of the world is forecasted (Intergovernmental Panel of Climate Change [IPCC], 2014; Ault et al., 2016; Stevenson et al., 2022). This complex situation turns even more pressing for arid and semiarid regions of the world, which may have been already experiencing abnormal droughts (Woodhouse et al., 2010). Globally, agriculture uses 70% of the available freshwater, and coupled with population growth and food demands, this implies a potential increase in agricultural production by 70% for the year 2050 (The World Bank, 2023). Therefore, agriculture urgently needs to implement water-saving irrigation strategies to improve crop water productivity (CWP), defined as "the ratio of crop yield to water consumed by the plant" (Heydari, 2014; Kilemo, 2022).

Deficit irrigation is the deliberate manipulation of irrigation in which water volumes are applied below the plant´s water optimal requirements (Ferere & Soriano, 2007); its implementation can increase CWP without providing additional water and is especially useful when the value of harvest is low, but the value of water is high (Abdelkhalik et al., 2019). Deficit irrigation consists of different schemes, such as regulated deficit irrigation (RDI) and sustained deficit irrigation (SDI) (Chai et al., 2016; Singh et al., 2021; Yang et al., 2022). RDI is a scheduling method that consists of the variable application of crop irrigation in specific stages of plant development, usually focusing on water volumes that are under the optimal plant growth requirements for specific phenological stages (Endalu & Temesgen, 2020; Yang et al., 2022). In contrast, SDI applies below-optimal water volumes during each irrigation event for the crop cycle (Chalmers, 2007). RDI and SDI have become efficient irrigation practices to optimize the CWP of different crops, such as vegetables and fruit trees (Parra et al., 2009; Hassan et al., 2021).

Given the short life cycles of pulses and their importance to global food security, it is critical to quantify the relevance of RDI and SDI to promote increases in their CWP. Successful applications of RDI and SDI in pulses, such as common bean (*Phaseolus vulgaris* L.) (Simsek et al., 2011) and pea (*Pisum sativum* L.) (Hirick et al., 2014), had led to enhance CWP. However, for chickpea (*Cicer arietinum*, L.), the third most intensively established legume globally, few reports have tested the advantage of applying RDI and SDI irrigation strategies (Hirich et al., 2011; Hirich et al., 2014; Douh et al., 2021). Studies suggest that RDI can induce significant differences in biomass yield. In chickpeas, induced drought stress at a level of 50% of crop evapotranspiration (ETc) during the vegetative period produced higher yields (6.5 t ha^{-1}) than under full irrigation (4.9 t ha^{-1}) (Hirich et al., 2014; Douh et al., 2021). Effects were the highest during the vegetative period compared with the flowering and grain-filling stages. However, it is critical to determine whether a 50% reduction or other reductions in ETc may further enhance CWP and other productivity-related variables during the vegetative period. In contrast, non-stress conditions during the flowering and grain-filling stages allow plants to increase their photosynthetic rate and carbon translocation to reproductive organs, thus increasing productivity (Hirich et al., 2011; Hirich et al., 2014). Water stress applied at the mid-vegetative and seed-filling stages mitigates the reductions in plant yield, and in other productivity and yield variables (Douh et al., 2021).

In order to optimize RDI and SDI strategies in chickpeas and other crops, the local environmental conditions under which RDI and SDI are implemented should be characterized (Chai et al., 2016; Endalu & Temesguen, 2020; Singh et al., 2021; Yang et al., 2022). Therefore, testing RDI and SDI under different schemes of irrigation volumes and methodologies is critical to expand their applicability and implementation in the field. Because CWP varies considerably due to genotype and environment, RDI and

SDI strategies require precise knowledge of crop response to drought stress, thus improving rational management decisions (Chalmers, 2007; Geerts, 2009; Mekonnen, 2020). When applied in combination, SDI schemes could inform growers about safe quantities to under-irrigate a crop, and at the same time, RDI could shed light on the correct timing (phenology stage) of when a deficit should be imposed (Endalu, 2020).

We evaluated the effects of deficit irrigation on grain yield, plant height and weight, grain caliber, the number of pods and grains per plant, the harvest index, and CWP under different schemes of RDI and SDI in the Blanoro variety of chickpea at Baja California Sur in north-west Mexico; this state has the lowest average annual rain in Mexico (190 mm), and climatic records indicate a persistent reduction in rain volumes for the last decades due to regional climate change (Ochoa-Noriega et al., 2020; Secretaría de Medio Ambiente y Recursos Naturales [SEMARNAT], 2021; Servicio Meteorológico Nacional [SMN], 2021; Murray-Tartarolo, 2021). Our primary hypothesis was that RDI during vegetative growth would allow the maximization of CWP and, secondarily, that flowering and pod filling would demand full irrigation to avoid abortion and the undergrowth of grains. In conjunction, our results intend to guide the establishment and improvement schemes of RDI for chickpeas and other pulses growing in the semiarid regions of the world.

2.3. Materials and methods

2.3.1. Experimental site condition

Two experiments were conducted during two consecutive years (2020 and 2021) at the National Institute for Forestry, Agriculture and Livestock Research (INIFAP), Todos Santos Experimental Station, Baja California Sur, México (at 110° 09´ latitude N and 23° 25´ longitude W, and at 150 m above sea level (Figure 1).

The climate in this area is arid and hot, with a mean rainfall and temperature of 168.6 mm and 24.6 °C, with 60% of the annual rainfall occurring during the summer season (Ruiz et al., 2006; Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias [INIFAP], 2017). During the period in which the experiments were conducted, the temperature ranged from 10.55 to 32.34 °C, with a relative humidity between 51.89 and 67.99% (Table 1).

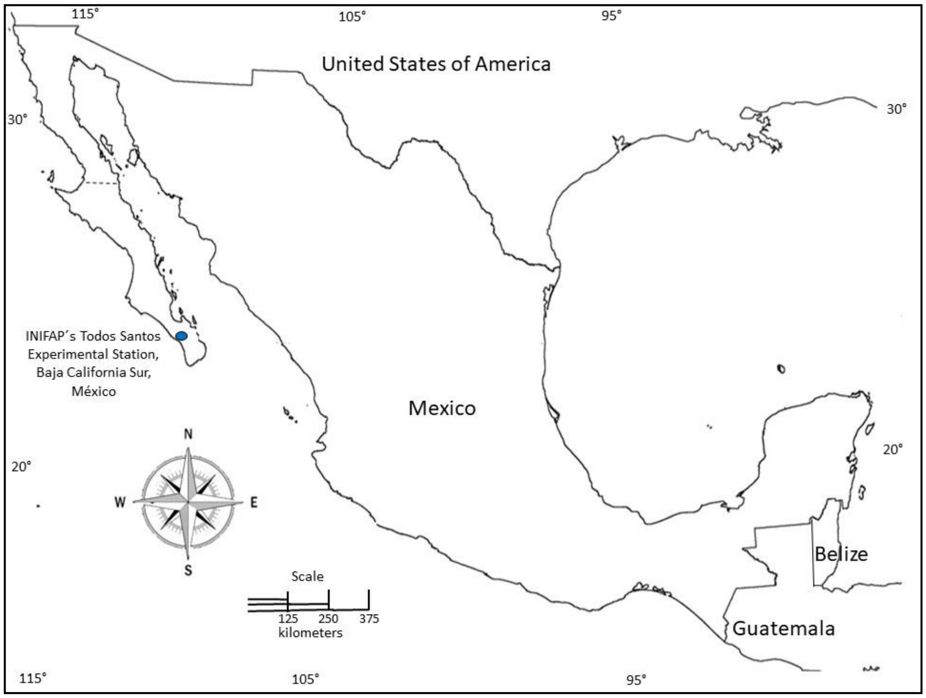

Figure 1. Todos Santos Experimental Station location (blue dot).

Table 1. Meteorological parameters for the growing seasons (monthly average for every variable) in the Todos Santos Experimental Station location, Baja California Sur, Mexico.

Meteorological parameter	Year 2020				Year 2021			
	January	February	March	April	January	February	March	April
Tmean *	18.82	19.06	20.46	18.85	17.78	18.28	19.23	22.26
Tmax *	27.81	27.57	29.49	28.08	27.50	27.83	29.43	32.34
Tmin *	10.83	10.55	11.90	10.94	10.62	10.63	10.48	12.73
Wind speed †	1.81	2.34	1.79	1.36	2.01	1.76	2.35	0.44
Rainfall events ‡	1.00	2.00	0.00	0.00	1.00	0.00	0.00	0.00
Rainfall §	3.00	30.00	0.00	0.00	36.00	0.00	0.00	0.00
RHmean ˜	62.00	64.30	61.52	67.99	59.10	61.51	51.89	48.32
RHmax ˜	84.30	88.83	86.85	90.17	82.08	86.89	82.62	82.42
RHmin ˜	37.84	39.77	36.77	40.40	33.82	34.99	24.27	20.00

*: °C, †: km h^{-1}, ‡: Days a $month^{-1}$, §: mm, ˜: %. Tmean= average temperature. Tmax = maximum temperature. Tmin = minimum temperature. RHmean = relative humidity (mean). RHmax = relative humidity (maximum). RHmin = relative humidity (minimum).

Both experiments were established on December 31 of each year, under drip-tape irrigation conditions in loamy sand soil with a pH equal to 8.08 and an electrical conductivity of 0.33 dS m^{-1}, with 11.7, 47.6, and 157 mg kg^{-1} of NO_3, P_2O_5, and K, respectively (Table 2). The soil was low in organic matter content

(0.91%) with a dry bulk density of 1.52 g cm^{-3}, a field capacity of 11.5%, and a permanent wilting point of 6.84%. Irrigation water was pumped from groundwater (the volume and quality of which is in Table 2).

Table 2. Soil and irrigation water properties at the Todos Santos Experimental Station, Baja California Sur, Mexico.

Soil Property *		Irrigation Water Properties	
Texture	Loamy sand	Salinity (dS m^{-1})	1.07
Salinity (dS m^{-1})	0.33	pH	7.62
pH	8.08	N-NO_3 (mg kg^{-1})	10.9
Field capacity (%)	11.50	K (mg kg^{-1})	0.39
Wilting point (%)	6.84	Ca (mg kg^{-1})	88.6
Bulk density (g cm^{-3})	1.52	Mg (mg kg^{-1})	36.1
Organic matter (%)	0.91	Na (mg kg^{-1})	78.2
Nitrogen NO_3 (mg kg^{-1})	11.70	SAR	1.92
Phosphorus-Bray (mg kg^{-1})	47.60	Classification of irrigation water	C2 S1
Potassium (mg kg^{-1})	157.00		

* Corresponding 0–30 cm soil profile. SAR: Sodium adsorption ratio.

2.3.2. Experimental plot establishment

The Blanoro variety of chickpeas used in this study was cultivated following the local management guidelines for this crop (INIFAP, 2017). We deployed a drip tape irrigation system with a drip tape caliber of 8000 µ, with droppers every 0.20 m for each tape meter and a flux of 4.98 l min^{-1} for each tape meter at an operating pressure of 8 psi. Seeds were sown one inch below the soil surface at a density of 14 seeds m^{-1} in every row, utilizing a double-row plantation. The space between rows was 0.40 m at each bed. Fertilization doses were 90-30-0 and applied in four parts, 15-30-0, 15-0-0, 30-0-0, and 30-0-0, at 17, 25, 34, and 51 days after sowing. The fertilizers used were urea (46-0-0) and mono ammonium phosphate (11-52-0). *Heliothis virescens* and *Liriomyza sativae*, the main pests present on the site, were controlled through the aspersion of abamectin and cyantraniliprole, at 500 and 150 mL ha^{-1}, respectively, dissolved in 270 L of water. Weeding was done manually from emergence until harvest in both cycles.

2.3.3. Treatments description and experimental design

A completely randomized block design testing eight irrigation treatments with four replications (Figure 2) was implemented, full irrigation (FI, ETc = 100%), sustained deficit irrigation (SDI_{75}, ETc = 75% during vegetative growth (VG), flowering (F), and pod-filling (PF), and six combinations of regulated deficit irrigation (RDI) varying across phenology, VG_{50} (ETc = 50%), VG_{75} (ETc = 75%), F_{50} (ETc = 50%), F_{75} (ETc = 75%), PF_{50} (ETc = 50), and PF_{75} (ETc = 75), were established each year (Table 3). The experimental treatment units consisted of three 4m long planting beds spaced 1.6 m apart (an area of 19.2 m^2). A one-meter-wide corridor separated contiguous treatments inside each block. For the duration of each stage of development, we calculated the growing degree days (GDD) through the equation 1:

$$GDD = [(Tmax + Tmin) / 2] - \text{Base temperature} \qquad \text{(eq. 1).}$$

Where: Tmax and Tmin are the maximum and minimum temperatures (°C) daily. The base temperature considered for the calculation was 5°C (Kumar et al., 2020).

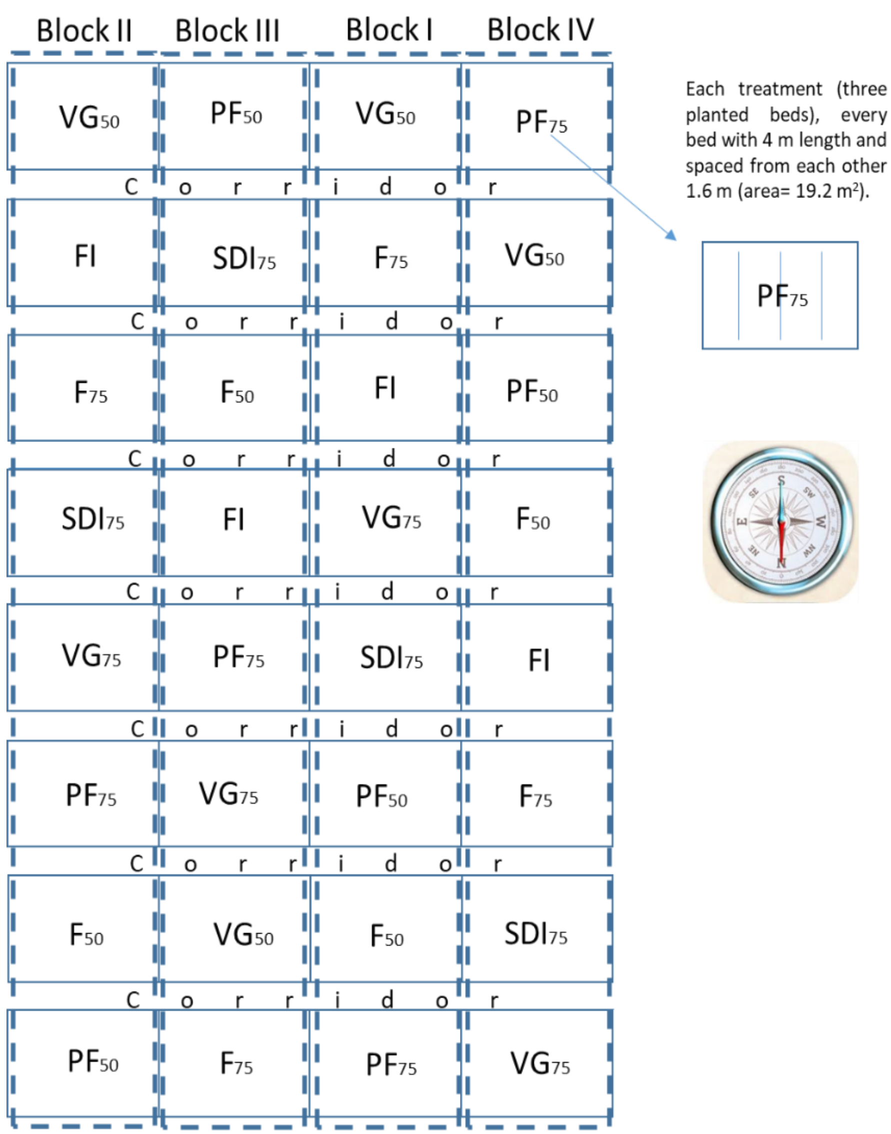

Figure 2. Experimental design for testing RDI and SDI on the Blanoro variety of Chickpea during years 2020 and 2021 in Todos Santos, Baja California Sur, Mexico. Treatments acronym in Table 3.

Table 3. Deficit irrigation treatments applied to chickpeas for two consecutive years (2020 and 2021) in Todos Santos, Baja California Sur, Mexico.

Treatments	**Treatments Description**				
	G	**VG**	**F**	**PF**	**S**
FI	Irrigation for germination for all treatments	100% ETc	100% ETc	100% ETc	No irrigation applied in all treatments
VG_{50}		50% ETc	100% ETc	100% ETc	
VG_{75}		75% ETc	100% ETc	100% ETc	
F_{50}		100% ETc	50% ETc	100% ETc	
F_{75}		100% ETc	75% ETc	100% ETc	
PF_{50}		100% ETc	100% ETc	50% ETc	
PF_{75}		100% ETc	100% ETc	75% ETc	
SDI_{75}		75% ETc	75% ETc	75% ETc	
Stage duration	0–10 days 149 GDD	10–33 days 149–506 GDD	33–56 days 506–811GDD	56–81 days 811–1189 GDD	81–112 days 1189–1655 GDD

Germination (G), vegetative growth (VG), flowering (F), pod-filling (PF), and senescence stages. RDI = regulated deficit irrigation. ETc = crop evapotranspiration. FI = full irrigation application of 100% ETc during VG, F, and PF. SDI_{75} = sustained deficit irrigation applying 75% of ETc during VG, F, and PF. VG_{50} = RDI applying irrigation equivalent to 50% of ETc in VG. VG_{75} = RDI applying irrigation equivalent to 75% of ETc in VG. F_{50} = RDI applying irrigation equivalent to 50% of ETc in F. F_{75} = RDI applying irrigation equivalent to 75% of ETc in F. PF_{50} = RDI applying irrigation equivalent to 50% of ETc in PF. PF_{75} = RDI applying irrigation equivalent to 50% of ETc in PF. GDD = growing degree days.

2.3.4. Irrigation scheduling and system

To promote seed germination, irrigation was applied continually until the space that spanned between the drip tape to where the seeds were located was fully wetted (0.20 m). After this initial period, the irrigation water requirement (IWR) between the two consecutives irrigation events was determined using the equation 2:

$$IWR = (ETc - Pe) / Ef \qquad \text{(eq. 2)}$$

Where ETc is the crop evapotranspiration (mm), and Pe is the effective precipitation (mm), which was determined using a Hellman pluviometer with a collection area of 400 cm^2; this pluviometer incorporates an 880 cm^3 inner aluminum collector vessel. Ef is the irrigation efficiency with a value of 0.85 (Hirich et al., 2011). The ETc was calculated from the reference evapotranspiration (ETo) and crop coefficient (Kc) with values of 0.3, 0.75, and 0.22 for the VG, F, and PF stages for the first year and 0.43, 1.05, and 0.31, for the same stages, respectively, for the second year. Figure 3 shows the meteorological records for both years (2020 and 2021).

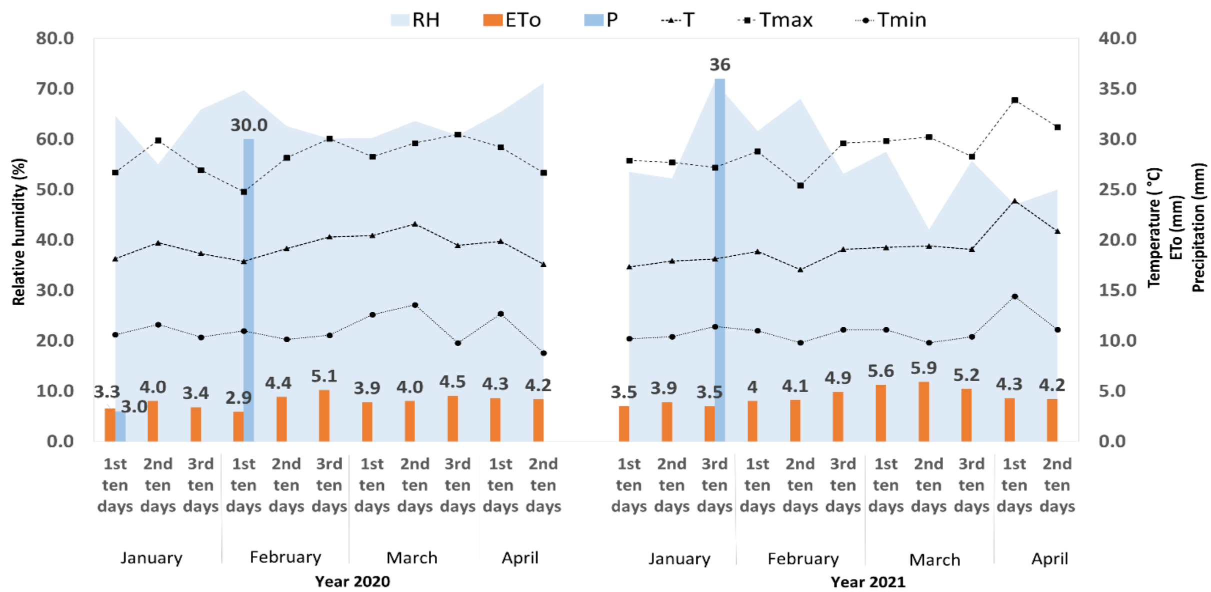

Figure 3. Relative humidity (RH; %), ten-day reference evapotranspiration (ETo; mm), precipitation (P; mm), average temperature (T; °C), and maximum (Tmax; °C) and minimum (Tmin; °C) temperatures during two consecutive years of evaluation.

Table 4. Deficit irrigation treatments and water volume accumulated by growth stage and total irrigation in chickpeas during two consecutive years of experiments (2020 and 2021) at Todos Santos, Baja California Sur, Mexico.

Treatments	Water volume accumulated (m^3 ha^{-1}) by growth stage and total irrigation (Ti)						
	G	VG	F	PF	S	Ti	% with respect to FI
			Year 2020				
FI	273.86 ‡	393.22 ‡	244.6	95.10	0.0	1006.78	100
VG_{50}	273.86	346.61	244.6	95.10	0.0	960.17	95.3
VG_{75}	273.86	369.91	244.6	95.10	0.0	983.41	97.6
F_{50}	273.86	393.22	122.30	95.10	0.0	884.48	87.8
F_{75}	273.86	393.22	183.45	95.10	0.0	945.63	93.9
PF_{50}	273.86	393.22	244.60	47.55	0.0	959.23	95.2
PF_{75}	273.86	393.22	244.60	71.32	0.0	983.00	97.6
SDI_{75}	273.86	369.91	183.45	71.32	0.0	897.84	89.1
			Year 2021				
FI	514.04	457.76 ‡	353.31	172.43	0.0	1497.54	100
VG_{50}	514.04	408.87	353.31	172.43	0.0	1448.65	96.7
VG_{75}	514.04	433.31	353.31	172.43	0.0	1473.09	98.3
F_{50}	514.04	457.76	176.65	172.43	0.0	1320.88	88.2
F_{75}	514.04	457.76	265.25	172.43	0.0	1409.21	94.1
PF_{50}	514.04	457.76	353.31	86.21	0.0	1411.32	94.2
PF_{75}	514.04	457.76	353.31	129.38	0.0	1454.49	97.1
SDI_{75}	514.04	433.31	265.25	129.38	0.0	1341.98	89.6
Stage duration	0–10[1] 0-149[2]	10–33[1] 149–506[2]	33–56[1] 506–811[2]	56–81[1] 811–1189[2]	81–112[1] 1189–1655[2]		

Germination (G), vegetative growth (VG), flowering (F), pod-filling (PF), and senescence stages. RDI = regulated deficit irrigation. For treatment´s key description see Table 3. GDD = growing degree days. ‡: treatment´s water volume considering rain. [1] In days. [2] In growing degree days.

ETo was calculated using the ETo Calculator software (Raes, 2012) from meteorological data obtained from local measurements (HOBO data logger MX2301A, Bourne, MA, USA). Instruments were installed aside our experimental plot and programmed to record the minimum, maximum, and mean daily values of temperature and relative humidity. In addition, the daily mean wind speed, and total hours of sunlight during each experimental season were accessed from reports published on the Meteoblue website (Meteoblue, 2022). Irrigation was applied, on average, every seven days. Table 4 shows the irrigation accumulated for every treatment by growth stage in both years. In the first experimental year, two rain events occurred on January 1 (3 mm) and February 3 (VG stage) (30 mm). During the second experimental year, one rain event occurred on January 29 (36 mm) during the VG stage (Figure 3).

2.3.5. Response variables

Response variables (Table 5) were measured in the harvest stage (physiological maturity), which occurred 112 days (1655 growing degree days) after planting. Plant height (H) was determined inside the central bed (4.8 m^2). Subsequently, the total number of plants in this area was hand harvested and stored in paper bags to obtain dry mass sampling through shade-drying in the lab. Later, a sub-sample of ten plants was randomly selected from each treatment to determine the average plant dry weight (PDW), pods per plant (PP), and grains per plant (GP). Sub-sample data plus the remaining content in each treatment´s paper bag was utilized for grain yield (GY), in kg m^{-2}, and to obtain the sample total dry weight as biological yield (BY) in kg m^{-2}; subsequently, GY was converted to kg ha^{-1}. GY in kg m^{-2} divided by the biological yield was utilized to estimate the harvest index (HI). For each treatment, the grain caliber (Cal) was determined as the number of grains in 30 grams. Finally, CWP was calculated as the total grain yield for each treatment divided by the total quantity of water used in the whole crop life cycle.

Table 5. Response variables of chickpea deficit irrigation experiments during two consecutive years (2020 and 2021) at Todos Santos, Baja California Sur, Mexico.

Variable	Symbol	Unit	Mean value ± Standard deviation
Grain yield	GY	kg ha^{-1}	903.33 ± 196.09
Grain caliber	Cal	grains in 30 g	47.69 ± 3.38
Plant height	H	m	0.40 ± 0.02
Plant dry weight	PDW	g $plant^{-1}$	13.18 ± 1.94
Number of pods per plant	PP	-	7.96 ± 1.23
Number of grains per plant	GP	-	9.18 ± 1.65
Harvest index	HI	-	0.44 ± 0.04
Crop water productivity	CWP	kg m^{-3}	0.78 ± 0.17

2.3.6. Data analysis

The mathematical model for the analysis of variance (ANOVA) employed is shown in equation 3:

$$Y_{ijk} = \mu + Y_i + T_j + B_k + YT_{ij} + YB_{(i)k} + E_{(i)jk} \qquad \text{(eq. 3)}$$

Where Y_{ijk} is the response variable measured on the $_{ijk}$ experimental unit (plot), μ is the overall mean, Y_i is the effect of the $_i$th year, T_j is the effects of the $_j$th treatment, $B_{(i)k}$ is the effect of the block within the $_i$th year, YT_{ij} is the interaction of the $_i$th level of Y with the $_j$th level of T, and $E_{(i)jk}$ is the experimental error. Statistical analyses were conducted with the procedure analysis of variance (PROC ANOVA) in version 9.3 of the SAS software, (Statistical Analysis System [SAS], 2011). We applied the Fisher least significance difference test (MEAN LSD) at the 5% alpha threshold for the detection of a significant trend. The description and classification of treatments were also executed in the SAS 9.3 software, with a principal component (PROC PRINCOM) and cluster analysis (PROC CLUSTER) with the AVERAGE method as the grouping criteria.

2.4. Results

2.4.1. Inter-year variability and treatment effect on our experimental data

Grain caliber, plant height, dry weight, harvest index, and CWP differed (p < 0.01) between experimental years (Table 18, Supplementary 1). A higher Kc was factored into the estimate of the ETc in the second year, leading to an increase in grain caliber, plant height, and dry weight but reducing the harvest index and CWP (Table 19 in Supplementary 1). The experimental treatments influenced all variables (p < 0.01, Table 18 in Supplementary 1). Plant height interaction between years and treatments varied, but no other variable did (p < 0.01, Table 18 in Supplementary 1).

2.4.2. Grain yield and quality

The highest grain yield was obtained in the treatments FI, VG_{75}, F_{75}, and PF_{75} (Figure 4A), with no statistical differences among them ($p \geq 0.05$, LSD). A restriction in irrigation equal to 75 ETc (VG_{75}) did not limit the grain yield with respect to pod-filling and flowering treatments (PF_{75} and F_{75}, respectively) (Table 6); however, the water deficit did limit productivity by 11.5 and 15.1%, respectively, in the latter treatments.

Grain caliber was highest at PF_{50} with 52.7 grains in 30 g (Figure 4B). The rest of the treatments showed no differences in grain caliber ($p \geq 0.05$, LSD), ranging between 46.0 to 48.7 grains at 30 g. Notably, water deficit during both flowering and pod filling affected grain caliber (Table 6), but a strong restriction of irrigation in the pod filling stage (PF_{50}) had the greatest impact on grain caliber.

In Figures 4A y 4B, more intense blue color in box plot indicates higher total irrigation volume, and more intense red color in box plot indicates lower total irrigation volume.

Table 6. Differences (%) in grain yield (GY) and grain caliber (Cal) among irrigation treatments.

Treatments	**Grain yield**	
	*** kg ha^{-1}**	**% with respect to FI**
VG_{75}	1124.8 ± 264.3	101.8
FI	1104.3 ± 246.2	100.0
PF_{75}	978.0 ± 150.9	88.5
F_{75}	937.6 ± 265.0	84.9
SDI_{75}	817.3 ± 162.2	74.0
PF_{50}	799.6 ± 150.3	72.4
VG_{50}	776.5 ± 221.2	70.3
F_{50}	688.2 ± 167.1	62.3
	Grain caliber	
	*** grain 30 g^{-1}**	**% with respect to FI**
PF_{50}	52.7 ± 6.7	113.0
F_{50}	48.7 ± 3.6	104.5
F_{75}	47.9 ± 5.2	102.7
SDI_{75}	46.9 ± 2.1	100.6
VG_{75}	46.7 ± 0.7	100.2
FI	46.6 ± 2.8	100.0
PF_{75}	46.5 ± 1.9	99.7
VG_{50}	46.0 ± 3.5	98.7

Vegetative growth (VG), flowering (F), and pod-filling (PF) stages in chickpea crop. RDI = Regulated deficit irrigation. ETc= Crop evapotranspiration. FI = full irrigation application of 100% of ETc during VG, F, and PF. SDI_{75} = sustained deficit irrigation applying 75% of ETc during VG, F, and PF. VG_{50} = RDI applying irrigation equivalent to 50% of ETc in VG. VG_{75} = RDI applying irrigation equivalent to 75% of ETc in VG. F_{50} = RDI applying irrigation equivalent to 50% of ETc in F. F_{75} = RDI applying irrigation equivalent to 75% of ETc in F. PF_{50} = RDI applying irrigation equivalent to 50% of ETc in PF. PF_{75} = RDI applying irrigation equivalent to 50% of ETc in PF. *: Mean ± standard deviation.

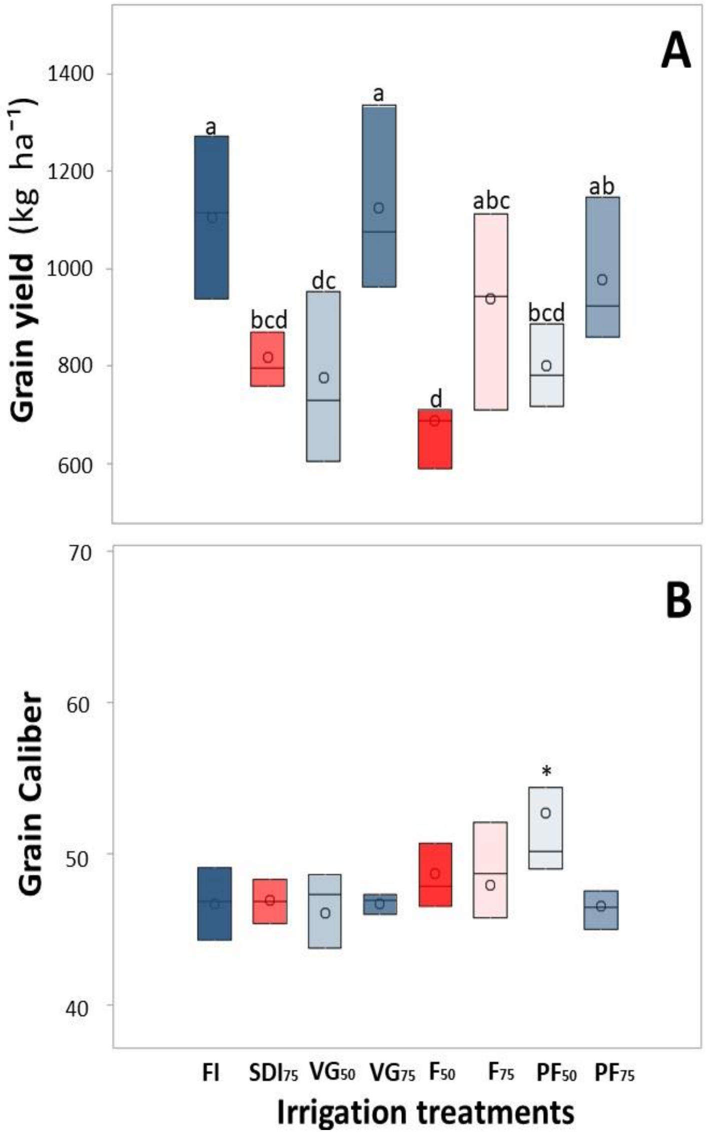

Figure 4. A) Grain yield and B) caliber (grains 30 g^{-1}) of chickpea grown using different irrigation treatments in Todos Santos, Baja California Sur, Mexico. Vegetative growth (VG), flowering (F), and pod-filling (PF) stages. RDI = regulated deficit irrigation. FI = full irrigation application of 100% ETc during VG, F, and PF. SDI_{75} = sustained deficit irrigation applying 75% of ETc during VG, F, and PF. VG_{50} = RDI applying irrigation equivalent to 50% of ETc in VG. VG_{75} = RDI applying irrigation equivalent to 75% of ETc in VG. F_{50} = RDI applying irrigation equivalent to 50% of ETc in F. F_{75} = RDI applying irrigation equivalent to 75% of ETc in F. PF_{50} = RDI applying irrigation equivalent to 50% of ETc in PF. PF_{75} = RDI applying irrigation equivalent to 50% of ETc in PF. [abcd] : different letters among treatments indicate significant difference ($p \leq 0.05$, LSD). More intense blue color in box plot indicates higher total irrigation volume, and more intense red color in box plot indicates lower total irrigation volume.

2.4.3. Plant growth

The FI, VG_{75}, and PF_{75} treatments had the largest effect on plant height (Figure 5A) ($p \leq 0.05$, LSD); the rest of the treatments were not associated with a difference in plant height. The VG_{50}, F_{50}, and PF_{50} treatments produced shorter plant heights (between 9.4 and 11.7%, Table 7) than FI. The FI, VG_{50}, VG_{75}, and PF_{75} treatments were associated with the highest plant dry weight values (Figure 5B), while the F_{50} and PF_{50} treatments produced plants with less weight (between 22 and 23%; Table 7). The number of pods per plant and grains per plant (Figures 5C, 5D) was higher in the VG_{75} treatment. Plant dry weight, pods per plant, and grains per plant were most sensitive to the combined effect of the irrigation restriction implemented during the critical stage; this is the application of the PF_{50} and F_{50} treatments (Table 7).

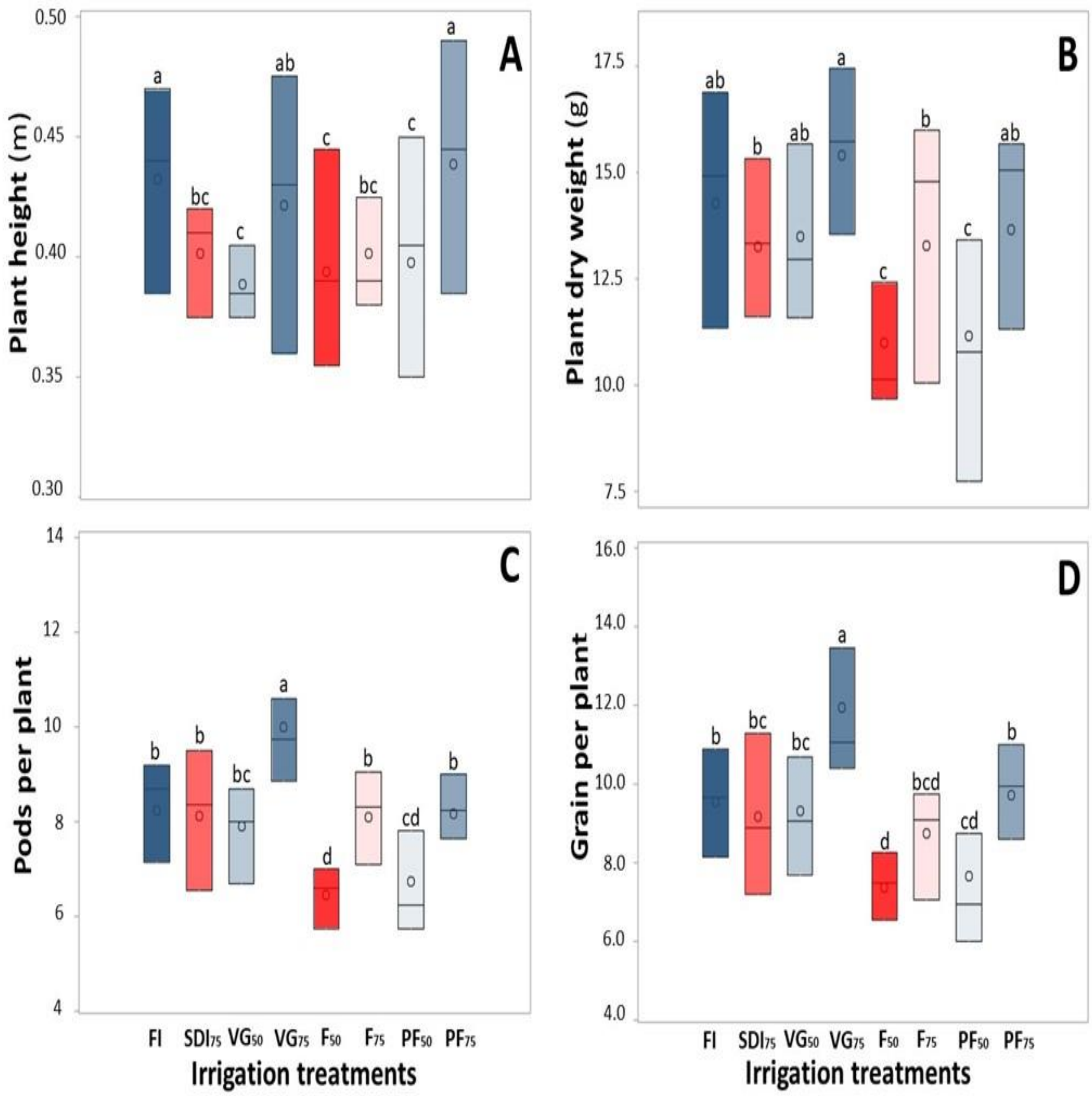

Figure 5. A) Plant height, B) plant dry weight, C) pods per plant, and D) grains per plant of chickpea under different irrigation treatments at Todos Santos, Baja California Sur, Mexico. Vegetative growth (VG), flowering (F), and pod-filling (PF) stages. RDI = regulated deficit irrigation. FI = full irrigation application of 100% ETc during VG, F, and PF. SDI_{75} = sustained deficit irrigation applying 75% of ETc during VG, F, and PF. VG_{50} = RDI applying irrigation equivalent to 50% of ETc in VG. VG_{75} = RDI applying irrigation equivalent to 75% of ETc in VG. F_{50} = RDI applying irrigation equivalent to 50% of ETc in F. F_{75} = RDI applying irrigation equivalent to 75% of ETc in F. PF_{50} = RDI applying irrigation equivalent to 50% of ETc in PF. PF_{75} = RDI applying irrigation equivalent to 50% of ETc in PF. [abcd]: different letters among treatments indicate statistical significance ($p \leq 0.05$, LSD). More intense blue in box plot indicates higher total irrigation volume, and more intense red in box plot indicates lower total irrigation volume.

Table 7. Differences (%) in plant height (H), plant dry weight (PDW), pods per plant (PP), and grains per plant (GP) among irrigation treatments.

Treatments	Plant height		Treatments	Pods per plant	
	m *	% with respect to FI		pods *	% with respect to FI
FI	0.43 ± 0.04	100.0	VG_{75}	10.00 ± 1.88	121.2
PF_{75}	0.43 ± 0.05	100.0	FI	8.25 ± 1.28	100.0
VG_{75}	0.42 ± 0.06	97.6	PF_{75}	8.17 ± 1.35	99.0
F_{75}	0.40 ± 0.03	93.0	F_{75}	8.10 ± 1.68	98.1
SDI_{75}	0.40 ± 0.02	93.0	SDI_{75}	8.12 ± 1.55	98.4
PF_{50}	0.39 ± 0.05	90.6	VG_{50}	7.90 ± 1.44	95.7
F_{50}	0.39 ± 0.05	90.6	PF_{50}	6.73 ± 1.66	81.5
VG_{50}	0.38 ± 0.02	88.3	F_{50}	6.45 ± 0.84	78.1
	Plant dry weight			**Grains per plant**	
Treatments	**g ***	**% with respect to FI**	**Treatments**	**grains ***	**% with respect to FI**
VG_{75}	15.41 ± 2.62	107.9	VG_{75}	11.93 ± 1.99	125.1
FI	14.27 ± 2.95	100.0	FI	9.53 ± 1.73	100.0
PF_{75}	13.66 ± 2.94	95.7	PF_{75}	9.71 ± 1.77	101.8
VG_{50}	13.48 ± 2.71	94.4	SDI_{75}	9.16 ± 2.05	96.1
F_{75}	13.26 ± 3.64	92.9	VG_{50}	9.31 ± 1.85	97.6
SDI_{75}	13.26 ± 2.30	92.9	F_{75}	8.75 ± 2.22	91.8
PF_{50}	11.14 ± 3.84	78.0	PF_{50}	7.66 ± 2.27	80.3
F_{50}	10.99 ± 2.20	77.0	F_{50}	7.37 ± 1.54	77.3

Vegetative growth (VG), flowering (F), and pod-filling (PF) stages. RDI = regulated deficit irrigation. ETc= Crop evapotranspiration. FI = full irrigation application of 100% ETc during VG, F and PF. SDI_{75} = sustained deficit irrigation applying 75% of ETc during VG, F, and PF. VG_{50} = RDI applying irrigation equivalent to 50% of ETc in VG. VG_{75} = RDI applying irrigation equivalent to 75% of ETc in VG. F_{50} = RDI applying irrigation equivalent to 50% of ETc in F. F_{75} = RDI applying irrigation equivalent to 75% of ETc in F. PF_{50} = RDI applying irrigation equivalent to 50% of ETc in PF. PF_{75} = RDI applying irrigation equivalent to 50% of ETc in PF. *: Mean ± standard deviation.

2.4.4. Crop productivity

A higher value of harvest index was found in the VG_{75} and PF_{75} treatments (Figure 6A), while the PF_{50}, F_{50}, and F_{75} treatments were associated with lower harvest indexes (Table 8).

Crop water productivity value was the highest in the VG_{75}, FI, F_{75}, and PF_{75} treatments, while SDI_{75}, PF_{50}, F_{50}, and VG_{50} showed the lowest, and these did not differ in crop water productivity (Figure 6B). The treatments VG_{50}, F_{50}, and PF_{50} limited the yield of the crop to a greater extent, even more than SDI_{75}, even though a sustained deficit irrigation treatment was applied throughout the whole ontogeny of this crop (Table 8).

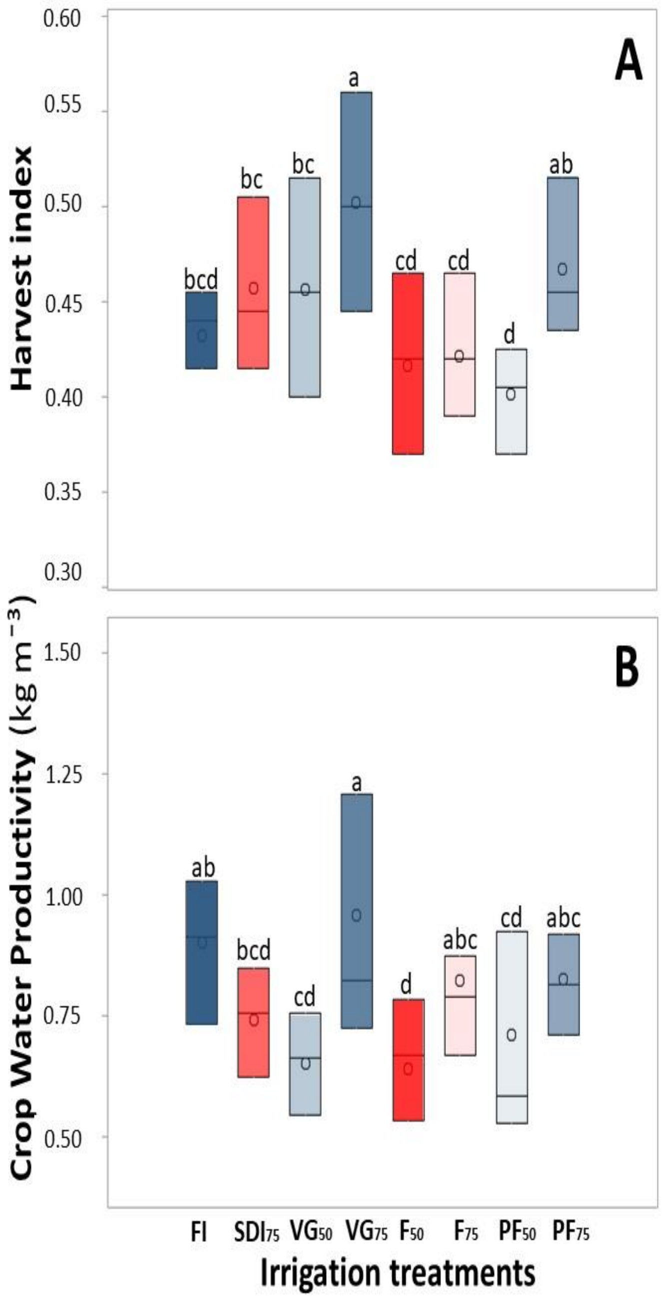

Figure 6. A) Harvest index and B) crop water productivity of chickpeas under different irrigation treatments at INIFAP´s Todos Santos Experimental Station, Baja California Sur, Mexico. Vegetative growth (VG), flowering (F), and pod-filling (PF) stages in chickpea crop. RDI = regulated deficit irrigation. ETc= Crop evapotranspiration. FI = full irrigation application of 100% ETc during VG, F, and PF. SDI_{75} = sustained deficit irrigation applying 75% of ETc during VG, F, and PF. VG_{50} = RDI applying irrigation equivalent to 50% of ETc in VG. VG_{75} = RDI applying irrigation equivalent to 75% of ETc in VG. F_{50} = RDI applying irrigation equivalent to 50% of ETc in F. F_{75} = RDI applying irrigation equivalent to 75% of ETc in F. PF_{50} = RDI applying irrigation equivalent to 50% of ETc in PF. PF_{75} = RDI applying irrigation equivalent to 50% of ETc in PF. [abcd] Different letter among treatments indicates statistical significance ($p \leq 0.05$, LSD). More intense blue in box plot indicates higher total irrigation volume, and more intense red in box plot indicates lower total irrigation volume.

Table 8. Differences (%) in harvest index (HI) and crop water productivity (CWP) among irrigation treatments.

Treatments	Harvest Index	
		% with respect to FI
VG_{75}	0.50 ± 0.07	116.2
PF_{75}	0.46 ± 0.05	106.9
VG_{50}	0.45 ± 0.06	104.6
SDI_{75}	0.45 ± 0.07	104.6
FI	0.43 ± 0.03	100.0
F_{75}	0.42 ± 0.05	97.6
F_{50}	0.41 ± 0.06	95.3
PF_{50}	0.40 ± 0.03	93.0
	Crop water productivity	
	* kg m^{-3}	% with respect to FI
VG_{75}	0.95 ± 0.34	105.5
FI	0.90 ± 0.22	100.0
F_{75}	0.82 ± 0.29	91.1
PF_{75}	0.82 ± 0.19	91.1
SDI	0.74 ± 0.12	82.2
PF_{50}	0.71 ± 0.23	78.0
VG_{50}	0.65 ± 0.14	72.2
F_{50}	0.64 ± 0.15	71.1

Vegetative growth (VG), flowering (F), and pod-filling (PF) stages. RDI = regulated deficit irrigation. ETc= Crop evapotranspiration. FI = full irrigation application of 100% ETc during VG, F and PF. SDI_{75} = sustained deficit irrigation applying 75% of ETc during VG, F, and PF. VG_{50} = RDI applying irrigation equivalent to 50% of ETc in VG. VG_{75} = RDI applying irrigation equivalent to 75% of ETc in VG. F_{50} = RDI applying irrigation equivalent to 50% of ETc in F. F_{75} = RDI applying irrigation equivalent to 75% of ETc in F. PF_{50} = RDI applying irrigation equivalent to 50% of ETc in PF. PF_{75} = RDI applying irrigation equivalent to 50% of ETc in PF. *: Mean ± standard deviation.

2.4.5. Multivariate classification and description for irrigation treatments

Data were summarized via principal component analysis (PCA) (Table 9). The first two main components (PC1 and PC2) accounted for 84.40% of the total variance, PC1 alone accounting for 47.0%. PC1 was defined as a component capturing the variability of grain yield, plant traits, and accumulated irrigation, as shown by the high positive correlation of PC1 with grain yield (r = 0.62), plant dry weight (r = 0.99), pods per plant (r = 0.81), grains per plant (r = 0.77), total irrigation (r = 0.77), and the negative correlation of grain caliber (r = −0.85). On the other hand, PC2 explained 37.4% of the variance and was positively related to plant height, CWP, and harvest index.

Figures 7A and 7B show the distribution of the variables and treatments in the first two principal components. Notably, the treatments evaluated in 2020 presented lower total irrigation, which limited plant dry weight, grains per plant, pods per plant, grain caliber, and grain yield in comparison with the treatments evaluated in 2021. Additionally, the 2020 treatments were associated with greater plant height, CWP, and harvest index. When integrating the information via cluster analyses across the years, VG_{75} formed a cluster on its own during 2020 (Figure 8A), but aggregated with FI during 2021 (Figure 8B).

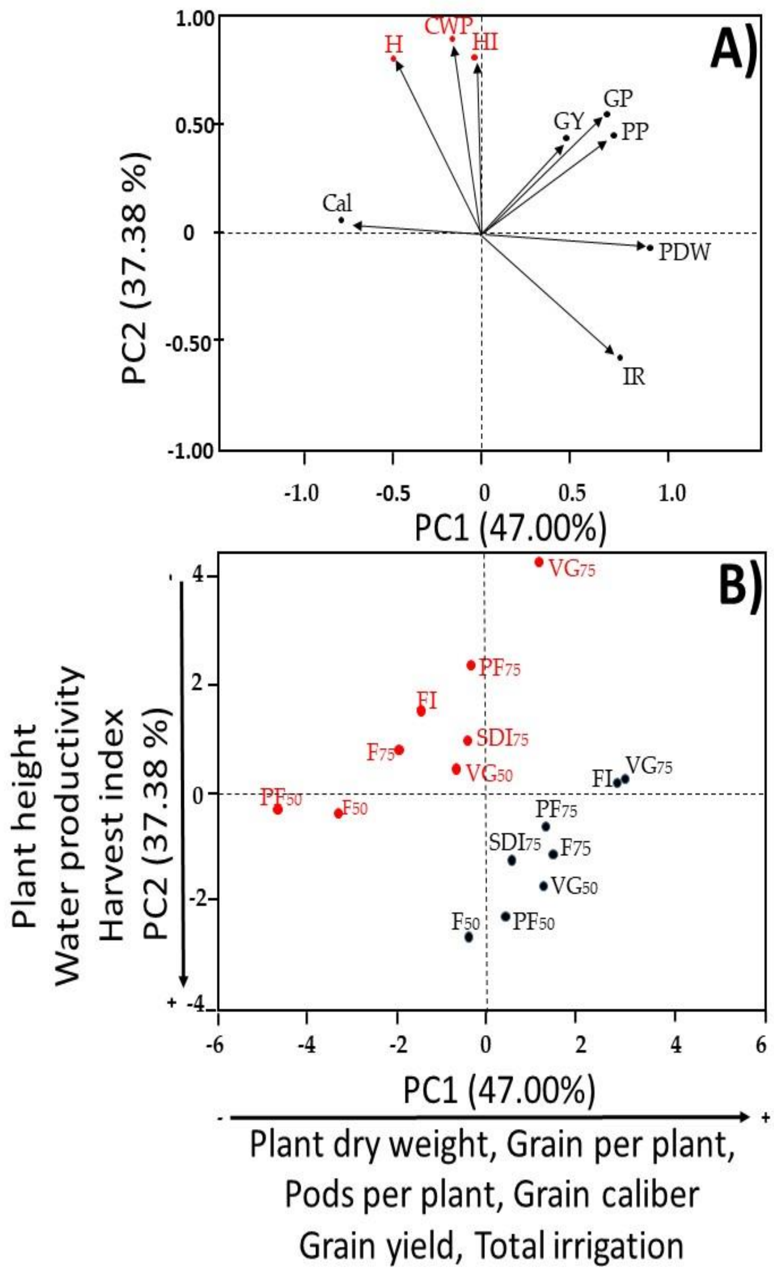

Figure 7. A) Variable distribution and B) irrigation treatments distribution across the two principal components. Vegetative growth (VG), flowering (F), and pod-filling (PF) stages. RDI = regulated deficit irrigation. ETc= Crop evapotranspiration. FI = full irrigation application of 100% ETc during VG, F, and PF. SDI_{75} = sustained deficit irrigation applying 75% of ETc during VG, F, and PF. VG_{50} = RDI applying irrigation equivalent to 50% of ETc in VG. VG_{75} = RDI applying irrigation equivalent to 75% of ETc in VG. F_{50} = RDI applying irrigation equivalent to 50% of ETc in F. F_{75} = RDI applying irrigation equivalent to 75% of ETc in F. PF_{50} = RDI applying irrigation equivalent to 50% of ETc in PF. PF_{75} = RDI applying irrigation equivalent to 50% of ETc in PF.

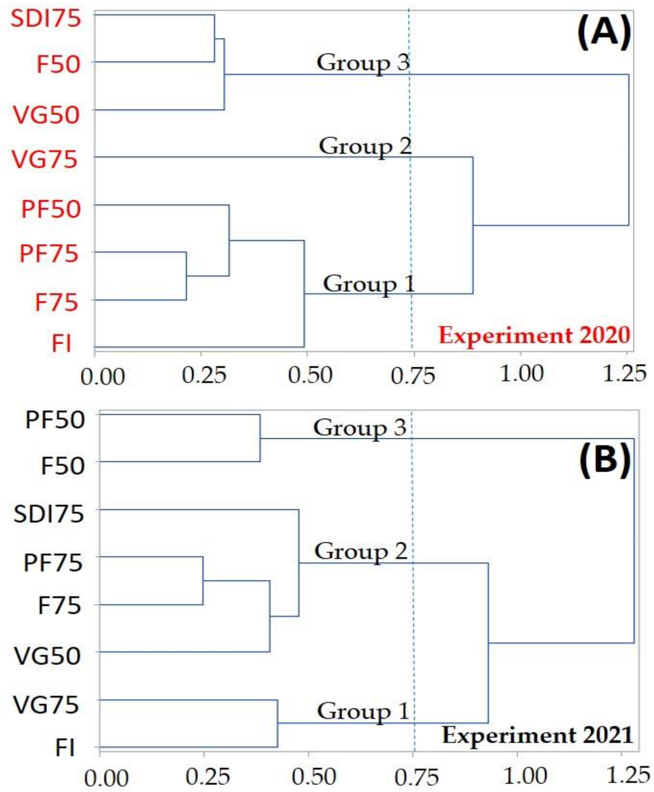

Figure 8. Treatment cluster analysis in A) experiment 2020 and B) experiment 2021. Vegetative growth (VG), flowering (F), and pod-filling (PF) stages. RDI = regulated deficit irrigation. FI = full irrigation application of 100% ETc during VG, F and PF. SDI_{75} = sustained deficit irrigation applying 75% of ETc during VG, F, and PF. VG_{50} = RDI applying irrigation equivalent to 50% of ETc in VG. VG_{75} = RDI applying irrigation equivalent to 75% of ETc in VG. F_{50} = RDI applying irrigation equivalent to 50% of ETc in F. F_{75} = RDI applying irrigation equivalent to 75% of ETc in F. PF_{50} = RDI applying irrigation equivalent to 50% of ETc in PF. PF_{75} = RDI applying irrigation equivalent to 50% of ETc in PF.

Table 9. Pearson correlation coefficients relating response variables with the two main principal components.

Variables	**Principal Components**	
	PC1	**PC2**
Grain yield (GY)	0.62 **	0.44
Grain caliber (Cal)	−0.85 **	0.02
Plant height (H)	−0.46	0.81 **
Plant dry weight (PDW)	0.99 **	-0.06
Pods per plant (PP)	0.81 **	0.47
Grains per plant (GP)	0.77 **	0.56
Crop Water productivity (CWP)	−0.19	0.91 **
Harvest index (HI)	−0.02	0.89 **
Total irrigation (IR)	0.77 **	−0.56
Eigenvalue	4.22	3.36
Variance Eigenvalue, %	47.00	37.40
Accumulated variance, %	47.00	84.40

PC1 = First principal component, PC2 = Second principal component. **: highly significant ($p \leq 0.01$).

2.5. Discussion

Our results agree with those of prior research on the regulated deficit irrigation (RDI) of chickpeas. As with those studies, we recommend implementing RDI during the vegetative growth stage, not during the flowering and pod filling stages, as it compromises crop yield (Hirich et al., 2011; Hirich et al., 2014; Douh et al., 2021). Our work provides additional insights into refining efficient practices of RDI to maximize crop yield, as we have tested the effect of a high number of irrigation combinations over eight critical productivity-related variables. In accordance with our main hypothesis, RDI during vegetative growth enhances CWP, but only when applying irrigation equivalent to 75% of ETc. This level of 75% RDI optimizes CWP without affecting productivity. In contrast, the application of SDI or RDI during the flowering and pod-filling stages compromised grain yield viability and reduced CWP. In conjunction, the potential for environmental, economic, and energetic savings can be inferred from this study.

2.5.1. Across-year differences in productivity, growth and grain yield, and quality

Because Kc varied by 25% across the years, the actual volume of water irrigated was 49% greater in the 2021 experimental year compared to that in the prior year. This difference was a product of climate differences between the years. The increased water volume in the year 2021 did not promote better grain yield, pods per plant, and grains per plant values. In the growing season of 2021, there was a slight increase in temperature and lower relative humidity, which increased ETc and vapor pressure deficits (Figure 3). This meteorological condition occurred between 50 and 90 days after planting (coinciding with the final flowering and pod-filling stages), thus reducing pollen production per flower in 2021, which, in turn, affected the percentage of germinated pollen, pod production, the number of seeds per pod, and the final crop yield. Similar impacts of drought on pollen production were found in other chickpea genotypes (Sivakumar et al., 1987; Devassirvatham et al., 2012; Fierros et al., 2017).

Observed differences in grain caliber and plant dry weight between the years with contrasting climate conditions were consistent with those found by other studies (Singh et al., 1991; Douh et al., 2021), as minor restrictions in irrigation increased seed weight, and with this, improve the caliber and increased the dry weight of the plants at harvest. In contrast, plant heights appeared to respond positively to low amounts of water restriction. However, plant height showed minimal differences or even slightly higher heights for plants under deficit irrigation (Douh et al., 2021). The harvest index, the proportion of grain produced per total weight of the plant, also varied between years. The harvest index was higher during

2020, implying a larger proportion of grain weight over plant dry weight. The increase in the harvest index when the irrigation water volumes were lower is concordant with previous research reporting that the water deficit applied in reproductive stages increases the allocation of plant resources in the reproductive organs, improving the productivity parameters in the crop (Kang et al., 2008). Given that the irrigation volume was lower by 49% in 2020 compared to 2021, and grain yield was not different across years, CWP was higher in 2020. These results are consistent with those of other studies in which chickpea crops were subject to lower total irrigation volume derived from a deficit irrigation application, and even when the grain production per plant was not optimal, CWP increased due to the application of a lower water volume (Hirich et al., 2014).

2.5.2. Effects of RDI and SDI treatments on chickpea grain yield and quality, plant growth, and productivity

The treatments that achieved higher grain yield were full irrigation or those that applied regulated deficit irrigation considering crop evapotranspiration of 75% during the vegetative growth (VG_{75}), flowering (F_{75}), or pod filling (PF_{75}) stages; the latter three treatments saved 24, 74, and 34 m^3 ha^{-1} of water on average in the two years of evaluation of (the average of the two growing seasons; Table 4). Oppositely, the lowest grain yield were produced by treatments in the VG_{50}, F_{50}, and PF_{50} stages (Table 6). The results of grain yield under full irrigation and regulated deficit irrigation during vegetative growth are consistent with those of other studies for the Desi chickpea, showing the best grain yield (6.7 t ha^{-1}) under irrigation restriction at the vegetative stages, followed by full irrigation treatment (4.9 t ha^{-1}) (Hirich et al., 2011) with irrigation volumes of 2300 m^3 ha^{-1} and 2750 m^3 ha^{-1}, respectively. Further evidence indicates that the grain yield performance under regulated deficit irrigation was reduced with respect to full irrigation, restricting grain yield by up to 38% (Sachdeva et al., 2022). In our study, grain yield from sustained deficit irrigation treatment was better than for treatments in VG_{50}, F_{50}, and PF_{50} due to the last ones experiencing a shorter period of stress but with more intensive irrigation restriction (50% of ETc in any crop stage studied).

Grain caliber was only affected by regulated deficit irrigation applied at 50% of the ETc in the pod-filling stage, which denotes once again the importance of not applying this irrigation strategy at this stage of development (Table 6); otherwise a reduction in the weight of the grains will be caused; this result agrees with that of previous findings (Hirich et al., 2014) but disagrees with that of another report (Sachdeva et al., 2022) in which the application of a water deficit during the reproductive phase, although at larger volumes than those used in our research, increased the translocation of resources to the reproductive organs.

Plant height was of a larger value under full irrigation treatments, and under those of regulated deficit irrigation applying 75% of the ETc in the vegetative growth and pod-filling stages. The treatments that applied 50% of the ETc in the three stages evaluated significantly reduced plant height (Table 7). Other studies found that height is mainly affected in the vegetative growth stage (a reduction of 12.1%) with respect to the reproductive stages (a decrease of 9.23%) (Olson et al., 2018). In our study, plant height under treatments of regulated deficit irrigation applying 50% of ETc during the vegetative growth and flowering stages diminished 11.7 and 9.4%, respectively. As plant height is a function of the water availability in any environment and is associated with biomass, it is expectable that regulated deficit irrigation applying 50% of ETc would reduce the investment in above-ground biomass (Olson et al., 2018). Therefore, plant height and plant dry weight were higher under full irrigation and were less affected under treatments with irrigation restriction in the vegetative growth (50 and 75% of ETc) stage, as well as in the pod filling stage applying 75% of ETc; likewise, more restrictive irrigation was associated to reductions in plant height, as found elsewhere (Ghassemi-Gplezani et al., 2013).

Pods per plant and grains per plant decreased as the water restriction increased (an application of 50% of ETc) in the flowering and pod-filling stages (Table 7); this situation is coincident with that found by Dogan et al. (2013) who reported a 3% decrease in the number of pods and grains per plant. The harvest index had less reductions under lower irrigation restrictions, which is consistent with the results of Dogan et al. (2013) and Sachdeva et al. (2022), and regulated deficit irrigation during the flowering stage or under substantial restrictions (50% of ETc) in the pod-filling stage impacted pods per plant and grains per plant to a greater degree.

Finally, CWP was reduced due to the application of regulated deficit irrigation in the flowering and pod-filling stages, because the biomass invested in reproductive structures was diminished as water stress promotes abortion or low grain yield. At the same time, in the case of regulated deficit irrigation during vegetative growth applying 50% of ETc also impacted CWP (Table 8). Other studies show that applications of 50% of full irrigation in the flowering stage in comparison to the pod filling stage generates significant reductions in CWP, the prior being more sensitive than the latter; so, in our study, flowering is confirmed as the most sensitive stage in which the application of regulated deficit irrigation impacts CWP more (Hirich et al., 2014).

2.5.3. Synthetic analyses

The principal component analysis successfully summarized the contributions of each of the variables with each component (Figure 7A), resulting in PC1 being associated with grain yield, plant dry weight, pods per plant, grains per plant, and total irrigation, but negatively associated with grain caliber. On the other hand, PC2 was positively related to plant height, CWP, and harvest index. Thus, it was observed that the treatments evaluated in 2020 were mainly associated with PC2, while the treatments evaluated in 2021 had stronger associations with PC1. Concerning the stages and levels of irrigation, in the years 2020 and 2021, treatments that applied irrigation at 50% of ETc during the flowering and pod-filling stages most affected the production of plants (Figure 7B). Another relevant contribution was the clusters formed by the year (Figures 8A and 8B), where VG_{75} was segregated as a relevant treatment with outstanding influence on both principal components (PC1 and PC2). These results are coherent with recommendations that the vegetative growth stage is the reference stage for applying regulated deficit irrigation strategies (Hirich et al., 2011). The reason is that regulated deficit irrigation modifies the patterns of allocation of the root and above-ground biomass and reaffirms the previous recommendation of not stressing the plant with this irrigation strategy during the flowering and pod-filling stages, thus enabling the plant to optimize its photosynthesis and carbon translocation to its reproductive organs, and increasing grain productivity (Hirich et al., 2011).

2.6. Conclusion

In concordance with our hypothesis, regulated deficit irrigation (i.e., crop irrigation in specific stages of plant development under the full requirement for optimal plant growth) applied in the vegetative stages is the best means to improve CWP. But the application of regulated deficit irrigation in the flowering and pod filling stages negatively impacts CWP; it is affected even more if the level of the reduction of irrigation reaches 50% of the crop evapotranspiration. This trend shows that the greater the restriction of irrigation, the more significant the impact on grain yield derived from a lower number of capsules and grains per plant. At the same time, CWP benefits from slight irrigation restrictions not reaching 50% of the crop evapotranspiration (at any crop stage). We consider it necessary to assess other levels of Kc in the stages of cultivation, which will allow an exploration of productive potential, refining the levels of 50 to 75% of ETc, seeking to increase grain yield and CWP, which would allow for the optimization of the implementation of regulated deficit irrigation schemes worldwide.

Chapter 3. UAV-derived thermal and multispectral imagery predicts grain yield and crop water productivity in chickpea (*Cicer arietinum* L.)

3.1. Abstract

Canopy temperature and vegetation indices can be used to estimate crop yield; however, the timing and irrigation practices may influence its performance. Using unmanned aerial vehicles-borne thermal and multispectral cameras, we quantified how the canopy temperature depression (CTD) and the normalized difference vegetation index (NDVI) can predict grain yield (GY) and crop water productivity (CWP) in chickpeas. CTD and NDVI were determined in a chickpea crop at the end of the vegetative growth, flowering, and pod-filling stages, using an experimental plot that tested different deficit irrigation treatments established in two kinds of plant arrangements (bed-system and single-row) under drip tape condition. The thermal infrared camera was a Zenmuse XT, mounted on a Matrice 100 drone. NDVI was estimated using a multispectral Parrot Sequoia camera mounted in a Mavic Pro drone; these images were utilized for building orthomosaics with Agisoft Metashape software. In addition, grain yield (GY) and crop water productivity (CWP) were quantified.

The results showed GY, CWP, and CTD differed among irrigation treatments ($p<0.01$); those established under the single-row system presented the highest range values in GY with 1429.9 to 1552.4 kg ha^{-1}, CWP with 0.53 to 0.60 kg m^{-3}, and CTD values of 6.6 to 7 °C, respectively. The NDVI was correlated with GY (r=0.76) and CWP (r=0.67), revealing that a decrease of 0.1 in this vegetation index could reduce 1,172 kg ha^{-1} and 0.4 kg m^{-3}, respectively. Similarly, CTD was correlated with GY (r=0.90) and CWP (r=0.81); a difference in one Celsius degree corresponds to a decrease of 212 kg ha^{-1} in GY and 0.07 kg m^{-3} in CWP. This investigation highlighted that CTD and NDVI measurements taken at the end of the flowering stage lead to better predicted GY in chickpeas produced under the single-row system (R^2=0.81 and R^2=0.72, respectively) and bed-system (R^2=0.79 and R^2=0.22, respectively). In conclusion, CTD and NDVI, determined from thermal and multispectral sensors mounted on UAVs, can be effectively used for predicting grain yield and water productivity in chickpea cultivation.

3.2. Introduction

Modern agriculture aims to improve crop productivity and resource use efficiency by applying new technologies (Arús, 2020). Precision Agriculture (PA), *i.e*., "the strategies to gather, process, and analyze spatiotemporal crop data, is a novel way to improve resource use efficiency, productivity, quality, profitability, and sustainability in agricultural production" (ISPA, 2021; Zeng et al., 2021). Given the unprecedented amount of remotely sensed information available for agricultural purposes, PA applications have expanded to include crop monitoring, irrigation management, nutrient application, disease, pest management, and yield prediction (Sishodia et al., 2020; Velusamy et al., 2022).

The recent developments in platforms, including low-altitude satellites and, most recently, low-cost Unmanned Aerial Vehicles (UAVs) coupled with multispectral and thermal cameras, allow the study of crop conditions on-demand by the producers (Ishimwe et al., 2014; Kumar et al., 2017; Parihar et al., 2021; Radocaj et al., 2023). UAV monitoring has gained importance in farm-level analysis because there is no satellite, at least with free access, that can monitor the terrain on a daily temporal frequency and with enough spatial resolution (Ihuoma & Madramootoo, 2017; Sagan et al., 2019; Filgueiras et al., 2019).

Multispectral images enable the calculation of vegetation indices (VIs) mathematical functions describing the reflected radiant flux in different spectral bands (Kadam *et al*., 2016). In a practical sense, VIs are optical measurements of vegetation canopy “greenness” employed to infer vegetation vigor (Huete, 2014).

The Normalized Difference Vegetation Index (NDVI) is the most widespread. NDVI correlates with the status of the photosynthetic apparatus (due to its use of a red band coinciding with the absorption peak of chlorophylls) and the content of foliar water (due to its use of a near-infrared absorption band coinciding with the absorption peak of water; Huang et al., 2021); thus allowing an indirect assessment of the crop physiological state throughout the growing seasons. NDVI is also commonly used to measure plant health and vigor and to detect areas with different hydraulic availability (Srivastava et al., 2022). Thus, understanding the spatio-temporal variability in NDVI can help detect and address irrigation needs in arid and semi-arid areas at the regional and local levels (Sankaran, 2015).

On the other hand, thermal cameras can record radiation emitted in the 8-14 μm spectral range, corresponding to the thermal infrared, and provide images representing temperature values per pixel. Thermal imagery can be used to quantify the plant’s canopy temperature, an indicator of tremendous value in plant physiology (Still et al., 2021), allowing the calculation of indices such as the canopy temperature depression (CTD), defined as the deviation of the temperature of the canopy of a plant concerning the ambient temperature. CTD has been related to the water status of the plants (Kumar et al., 2017). This type of technology can be a proxy for stomatal conductance measurements, thus helping to assess the physiological status of plants at different scales over short periods (Jones, 2004; Ishimwe et al., 2014). Thermal cameras can detect variations ranging between 0.7-7.0 °C in the canopy of plants subjected to water stress vs. healthy plants (Pineda et al., 2020). Thermal imagery can act as a proxy measurement for stomatal activity, an essential trait to estimate plant growth and development, as enhancements in stomatal conductance involve increases in carbon assimilation at the expense of more significant transpiration rates (Jones, 2014). In an analogous way as stomatal conductance is related to crop yield and tolerance to environmental stress (Prashar et al., 2013), and due to its strong correlation with leaf temperature (Milthorpe & Spencer, 1957; Pineda et al., 2021), thermal imagery can be associated with yield and productivity.

In chickpeas, Srivastava et al. (2022) compared the heat tolerance of chickpea (*Cicer arietinum* L.) varieties using their NDVI values, finding that Desi chickpeas are superior in heat tolerance to those of the Kabulis variety. Avneri et al. (2023) determined that morphological parameters (height, width, and volume) and vegetation indices estimated from UAV-acquired RGB images can be used to predict aerial biomass, leaf area index, and grain yield through the irrigation periods of chickpeas.

Purushothaman et al. (2015) associated the decrease in canopy temperature at the mid-reproductive stage (measurements between 59 and 82 days after planting) with grain yield in chickpeas under terminal drought. Each degree of decrease in canopy temperature increased grain yield by 293 kg. Also, Purushothaman et al. (2015) pointed out that a decrease in canopy temperature during the reproductive growth stage is associated with the soil's moisture level and can be used as an indicator of drought tolerance in chickpea cultivation. Thermal imaging systems, therefore, acted as a proxy of canopy transpiration in chickpeas, avoiding the limitations of the direct physiological measurements of this trait, as UAVs can record large areas in a frequent and rapid procedure.

Even when several authors have explored the link between multispectral and thermal imagery with productivity parameters in different crops, our knowledge still has limitations, particularly concerning the use of remotely sensed technologies to predict productivity under deficit irrigation strategies. For example, it is critical to evaluate the links between NDVI and thermal indices and productivity variables under agricultural water-saving strategies, such as partial root-zone drying (PDI), regulated deficit irrigation (RDI), and sustained deficit irrigation (SDI). Given the physiological manipulation imposed by these irrigation practices, is it possible to still predict GY and CWP using multispectral or thermal imagery? Can multispectral and thermal imagery detect differences in GY and CWP in different plant arrangements like bed systems or single rows? Also, as the deficit irrigation strategies modulate the leaf physiology to enhance grain productivity, comparing the predictability advantage of using multispectral or thermal imagery is critical. Given that these two indicators rely on a physiological basis of detecting leaf-dependent malfunctions due to water scarcity across large areas, it is possible to expect that both are equally efficient at predicting critical agronomic variables, such as grain yield (GY) and crop water productivity (CWP)? Finally, is the timing for recording remotely sensed information dependent on the phenological stage, and if it is, are the two types of imagery equally influenced by phenology?

Thus, in the present work, we compare the relative advantages of using remotely acquired thermal and multispectral images obtained with UAVs to monitor irrigation and predict GY and CWP in chickpea crops under different schemes of deficit irrigation and plant arrangement. Our results aim to guide the relative efficiencies of these two technologies in predicting long-term agronomic goals and provide a reference to define management practices directed to improve the prediction of crop productivity.

3.3. Materials and methods

3.3.1. Experimental site

The experimental plot was established at Todos Santos Experimental Station of the National Institute for Forestry, Agriculture and Livestock Research (INIFAP), Baja California Sur, Mexico (23° 25´ 06.84” latitude N, 110° 09´ 02.37” longitude W) at 150 meter above sea level. The soil in the site (profile 0-0.3 m) is loamy sand soil with a pH of 8.08, an electrical conductivity of 0.33 dS m^{-1}, with 11.7, 47.6, and 157 mg kg^{-1} of NO_3, P_2O_5, and K, respectively. The soil’s organic matter content was 0.91%, with a dry bulk density of 1.52 g cm^{-3}, a field capacity of 11.5%, and a permanent wilting point of 6.84%. Irrigation water was pumped from groundwater; its salinity was 1.07 dS m^{-1} with a pH of 7.62 and sodium adsorption ratio of 1.92. The climate in this area is arid and hot, with a mean temperature of 24.6 °C, annual rainfall of 168.6 mm, and 60% of the annual rainfall occurring during the summer season.

3.3.2. Experimental design and irrigation treatments

First, a randomized complete block design that tested eight irrigation treatments (Table 10) on *C. arientinum* cv. Blanoro under the condition of drip tape irrigation.

The treatments varied in the amount of water applied by growth stage linked to specific irrigation strategies (full or deficit irrigation) and plant spatial arrangements (bed system and single row). The specific crop stages of irrigation management were vegetative growth (VG), flowering (F), and pod-filling (PF), and irrigation volumes were based on different values of crop evapotranspiration (ETc) (Table 10).

Planting began on January 1, 2022, locating the seeds in previously wet soil and concluded with the harvest on April 13, 2022. To control for the effect of soil water and other possible artifacts on the imaging sets, we applied one over-irrigation treatment (at 125 % of the ETc; dark blue in Table 10), one full irrigation treatment (100% of ETc; middle blue), and several deficit irrigation treatments (75 % of ETc; light blue).

For watering, we employed a drip tape with a caliber of 8000 µ, with droppers every 0.20 m and a flux of 4.98 l min^{-1} at an operating pressure of 8 psi for each tape meter. Bed systems treatments were located within 1.6 m of terrain with a double-row of plants, obtained from 14 seeds m^{-1} in every row, and the space between rows was 0.40 m (Figure 9A). Treatments in single-row plants included 14 seeds m^{-1} in every row (Figure 9B).

All treatments received the same fertilization doses of 90-30-0. The fertilizers were urea (46-0-0) and mono-ammonium phosphate (11-52-0). *Heliothis virescens* and *Liriomyza sativae*, the main pests present on the site, were controlled through the aspersion of abamectin and cyantraniliprole, at 500 and 150 mL ha^{-1}, respectively, dissolved in 270 L of water. Weeding was done manually during the whole crop cycle.

On December 31, 2021, one rainfall event of 20 mm (200 m^3 ha^{-1}) occurred, this value according to the Hellman pluviometer (400 cm^2 collection area) installed in the location, which allowed sowing in wet soil on January 1, 2022. The germination stage required 15 days and the additional application of two irrigations, one on January 5, 2022, with a volume of 124.7 m^3 ha^{-1} and another on January 8, 2022, with 83.25 m^3 ha^{-1}. Table 20 in Supplementary 2 describes the dates, volumes applied for each treatment evaluated, and accumulated irrigation volumes by growth stage, as well as the duration of every stage considering growing degree days (GDD); GDD is a more accurate physiological estimate of crop development compared to calendar days alone (Cornell Institute for Climate Smart Solutions[CICSS], 2023). The GDD calculation was carried out with Equation 1, described in section 2.3.2.

Table 10. Irrigation treatments to test the association between yield and productivity with thermal and multispectral indices in chickpea Blanoro variety.

Treatments: Key	Treatments: Description (Irrigation strategy + Plant´s spatial arrangement)	Irrigation by treatment (% ETc) and crop stage‡: G*	VG	F	PF	Se	Total irrigation $m^3\ ha^{-1}$
OI-B	**Over-irrigation +** bed system with double row of plants	Same water volume for all treatments‡	125	125	125	No irrigation	3435.81
FI-B	**Full irrigation +** bed system with double row of plants		100	100	100		2830.24
RDI$_{VG}$-B	**Regulated deficit irrigation** applied in VG stage **+** bed system with double row of plants		75	100	100		2705.16
SDI-B	**Sustained deficit irrigation + bed** system with double row of plants		75	75	75		2224.66
FI-S	**Full irrigation +** plants in single row		100	100	100		2830.24
PDI$_{VG}$-S	**Partial root zone drying irrigation** applied during VG stage **+** plants in single row		75	100	100		2705.16
PDI$_{F}$-S	**Partial root zone drying irrigation** applied during F stage **+** plants in single row		100	75	100		2433.15
PDI$_{PF}$-S	**Partial root zone drying irrigation** applied during PF stage + plants in single row		100	100	75		2746.82

*G= germination, VG= vegetative growth, F= flowering, PF= pod-filling, Se= senescence. P= Partial root-zone drying irrigation. Dark, middle, and light blue colors indicate 125, 100 and 75 % of ETc applied in the specific growth stage. ‡Germination period considered an accumulated water volume of 407.95 $m^3\ ha^{-1}$. Senescence stage did not considered irrigation.

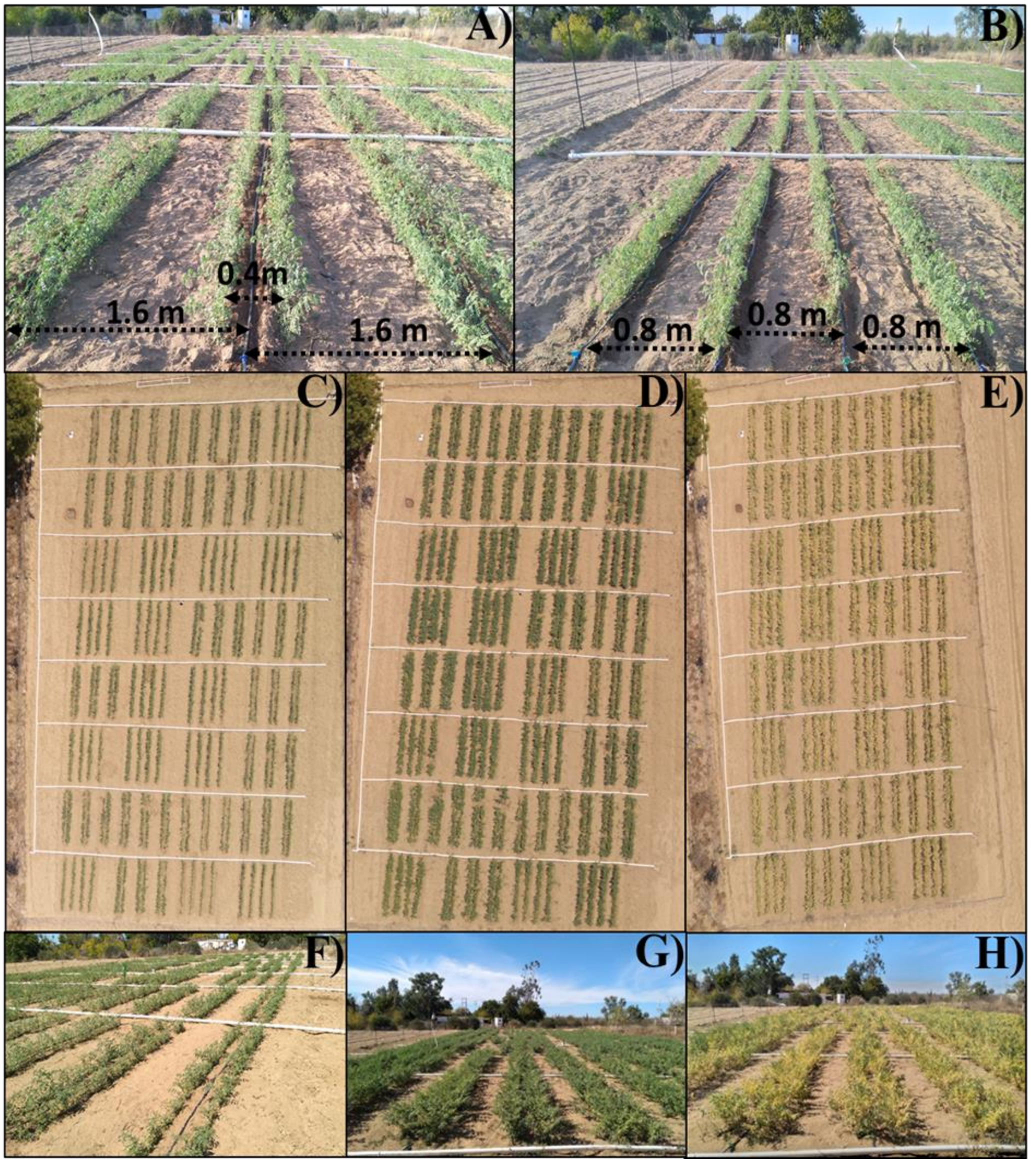

Figure 9. A) Chickpea crop under bed-system separated 1.6 m with double-row plants; the distance between plant rows was 0.40 m. B). Chickpea crop under single-row plants system separated 0.8 m. Images of the aerial and ground level of the experimental plot corresponding at the end of the vegetative growth (C and F; February 11, 2022), flowering (D and G; March 09, 2022), and pod filling (E and H; March 28, 2022) at Todos Santos Experimental Station-INIFAP, Baja California Sur, Mexico.

The criteria for the first two watering dates (See I-1 and I-2 irrigation events in Table 20 in Supplementary 2) is to apply enough water to reach the location of the seed to promote germination. Starting from the third irrigation, we estimate ETo through the ETo Calculator software (https://www.fao.org/land-water/databases-and-software/eto-calculator/es/) using the daily minimum, maximum, and average temperatures and relative humidity (see Figure 17A in Supplementary 2). These were obtained from local measurements made with a temperature and relative humidity datalogger

(HOBO Datalogger MX2301A, Bourne, MA, USA).

After ETo determination, we estimated the crop evapotranspiration (ETc, mm day^{-1}), utilizing equation 4, as a factor of reference evapotranspiration (ETo, in mm day^{-1}) and the crop coefficient (Kc, unitless) (Allen et al., 2006; Farg et al., 2012); for Kc values, we recognize that these are site-specific and vary by cultivar, however since local values were lacking, average values per growth stage derived from the evaluation of chickpeas in climates similar to that of our locality were used. The Kc values utilized were 0.43, 1.05, and 0.31 for the VG, F, and PF stages (FAO, 2006; Guevara et al., 2006; Hirich et al., 2011; Mbarek & Douh, 2015; Apáez et al., 2016).

$$ETc = ETo * Kc \quad \text{(eq. 4)}$$

Finally, the net irrigation, *i.e*., the amount of water applied to each treatment per each event ($N_{irrigation,}$ in mm day^{-1}), was obtained by equation 5:

$$N_{irrigation} = (ETc – Pe) / Ef, \quad \text{(eq. 5)}$$

Where the effective precipitation (Pe, in mm) was zero, because we did not have any recorded rain event after sowing, and we assumed the efficiency of the irrigation system (Ef) of 0.85 (Hirich et al., 2011). The behavior of ETo, ETc, $N_{irrigation}$, and Kc values is shown in Figure 17B in Supplementary 2.

3.3.3. Response variables

3.3.3.1. Grain yield (GY) and crop water productivity (CWP)

To determine the effect of the different treatments on crop performance, we measured grain yield (GY) in kg ha^{-1} and crop water productivity (CWP) in kg of grain m^3 of irrigation water at the harvest. GY was determined by harvesting all the grain presented in a three-meter-long central bed (4.8 m^2) with double plant rows. GY was determined for the two central three-meter-long rows (4.8 m^2) for treatments under a single-row system. CWP was calculated with equation 6 as the GY of each treatment divided by the total irrigation of each treatment (Ti, Table 20 in Supplementary 2).

$$CPW = GY/T_i \quad \text{(eq. 6)}$$

3.3.3.2. Image acquisition

The multispectral and infrared images were acquired between 11:00 and 13:00 local time at the end of the three growth stages: vegetative growth (Figure 9C and 9F), flowering (Figure 9D and 9G), and pod-filling (Figure 9E and 9H); the dates of each flight along with environmental data are in Table 11.

For multispectral image acquisition, we utilized a Parrot Sequoia camera (Parrot Group, Paris, France, https://www.parrot.com/en/support/documentation/sequoia) mounted in an unmanned aerial vehicle (model Mavic Pro, DJI Inc., Nanshan, SZ, China, https://www.dji.com/mx/mavic). For thermal-infrared image acquisition, we used a Zenmuse XT, FLIR System, Inc. camera (DJI Inc., Nanshan, Sz China, https://www.dji.com/mx/zenmuse-xt) mounted on a UAV Matrice 100 (DJI Inc, Nanshan Sz, China https://www.dji.com/mx/matrice100).

The UAV flights were carried out following pre-programmed flight plan software (Litchi https://flylitchi.com/). The flight mission for the multispectral camera was carried out at a flight altitude and speed of 20 m and 2 m s^{-1}, respectively. We obtained a single scene from the FLIR camera at a fixed altitude of 160 m.

The multi-spectral Parrot Sequoia equipment includes an RGB camera with a 4608 × 3456-pixel sensor and a focal length of 4.88 mm. The pixel size at 20 m height is 1.9 cm^2. It also has four cameras sensitive to the green (G, 550 wavelength, 40 nm bandwidth), red (R, 660 nm wavelength, 40 nm bandwidth), Red Edge (RE, 735 nm wavelength, 10 nm bandwidth), and near-infrared (NIR, 790 nm wavelength, 40 nm bandwidth) spectral bands, with a resolution of 1280 × 960, a focal length of 3.98 mm and a pixel size of 6.8 cm^2 at a flying height of 20 m.

From the thermal infrared scene, we determined canopy temperature (CT) and canopy temperature depression (CTD, Bhandari et al., 2021). The software FLIR Thermal Studio (https://www.flir.com.mx/products/flir-thermal-studio-suite/) was used to obtain temperatures from the image. CT average values for each treatment were obtained considering the temperatures inside the three-meter-long central bed (4.8 m^2). We determined CT from the two central three-meter rows (4.8 m^2) for treatments with a single row.

Finally, we determined canopy temperature depression (CTD) as the difference between CT and air temperature (Table 21 in Supplementary 2).

Table 11. Crop growth stage, air temperature, and relative humidity during image acquisition flights. Air temperature and humidity were measured at the time when the images were taken.

Date, hour	Growth stage	Air temperature °C	Relative humidity %
February 11, 2022, 11:55 a.m.	Vegetative growth (VG)	26.18	40.34
March 09, 2022, 11:59 a.m.	Flowering (F)	26.32	28.24
March 28, 2022, 12:28 p.m.	Pod-filling (PF)	29.22	33.35

3.3.3.3. Normalized vegetation index (NDVI) and canopy temperature depression (CTD)

The NDVI index was calculated by equation 7 (Silva et al., 2016):

$$NDVI= [\rho_{NIR} - \rho_{R}] / \rho_{NIR} + \rho_{R} \quad \text{(eq. 7)}$$

Where ρ_{NIR} and ρ_{R} are the reflectance in the spectral range of the near infrared and red, respectively.

NDVI data was obtained from 151 overlapped photos of the near-infrared and red bands from the Parrot Sequoia sensor to generate an orthophoto with Agisoft Metashape software (AGISOFT, 2021). The orthophoto was exported to QGIS 3.1 software (QGIS Development Team, 2022), and the NDVI calculation tool with the raster calculator was employed. From this set of calculations, the NDVI average value of each treatment was obtained, considering only pixel values inside the three-meter-long central bed (4.8 m^2) for the double plant rows system (Table 16 in Supplementary 2). For treatments under a single-row system, NDVI was determined in three meters long of the two central lines (4.8 m^2) (Table 22 in Supplementary 2).

3.3.3.4. Statistical analysis

3.3.3.4.1. Effects of irrigation treatments

The response of the crops to the different irrigation treatments was estimated using crop variables measured *in situ* (GY and CWP) and from remote sensors (NDVI and CTD) with images obtained with the aid of UAVs. We used the following model (equation 8) for the analysis of variance (ANOVA):

$$Y_{ijk} = \mu + T_i + B_j + E_{ij} \quad \text{(eq. 8)}$$

Where Y_{ijk} is the response variable measured on the $_{ij}$ experimental unit (plot), μ is the overall mean, T_i corresponds to the $_i$th water treatment (as in Table 10), B_j is the effect of the block, and E_{ij} is the experimental error. We applied the Fisher least significance difference test (LSD) at the 5% alpha threshold to detect a significant trend (The Concise Encyclopedia of Statistics [CES], 2008). We used several standard methods for the statistical relationship, such as Pearson's correlation test and regression models (Sedwick, 2012; KSU, 2023). We analyzed the average values of all treatments using principal component and cluster analysis. All the analyses were executed in SAS software version 9.3 (Cary, NC, USA).

3.4. Results

3.4.1. Response to different irrigation treatments

3.4.1.1 Grain yield and crop water productivity

There were statistical differences in GY, CWP, and CTD ($p < 0.01$, Table 23 in Supplementary 2). In GY, treatments FI-S, PDI_{VG}-S, PDI_F-S, and PDI_{PF}-S presented the most significant values (1430.0 to 1552.5 kg ha^{-1}), resulting in statistically equal among them. At the same time, OI-B, FI-B, RDI-B, and SDI-B were also equal to each other but inferior to the first group (730.6 to 989.2 kg ha^{-1}) (Figure 10A). For CWP, treatments that included simple rows of plants in combination with irrigation strategies (FI-S, PDI_{VG}-S, PDI_F-S, and PDI_{PF}-S) presented the most significant values (ranging from 0.53 to 0.6 kg m^{-3}) (Figure 10B), in comparison to bed planting system; the latter were equivalent to each other, but inferior (0.27 to 0. 39 kg of grain m^{-3}) to the single-row treatments. The application of ETc 75% through irrigation with partial root-zone drying, while contributing to 25% saving of required water, did not differ in GY and CWP compared to ETc 125 and 100%.

3.4.1.2. Canopy temperature depression (CTD) and normalized vegetation index (NDVI)

CTD corresponded to the ranking in GY and CWP across treatments: FI-S, PDI_{VG}-S, PDI_F-S, and PDI_{PF}-S presented lower difference temperature values (Figure 10C); *i.e.*, treatments with larger GY and CWP corresponded to lower values of CTD. NDVI did not show a significant difference across treatments, even though the values did show a trend of increasing values for larger irrigation in bed system (OI-B) or single-row system (FI-S, PDI_{PF}-S). NDVI mean values were also higher in the single-row sowing system (Figure 10D), except in the OI-B treatment, which shows values similar to single-row system treatments. However, the mean values were not statistically different (p>0.05). Single-row system treatments presented higher GY and CWP. CTD values were consistently lower in irrigation treatments that considered single-row system, independently of the ETc restriction applied, corresponding to lower CTD by growth stage (Figure 11A). NDVI did not have significant differences for treatments inside each growth stage or in the accumulated value across treatments. However, those considered single-row systems show slightly larger values in the VG and F stages (Figure 11B).

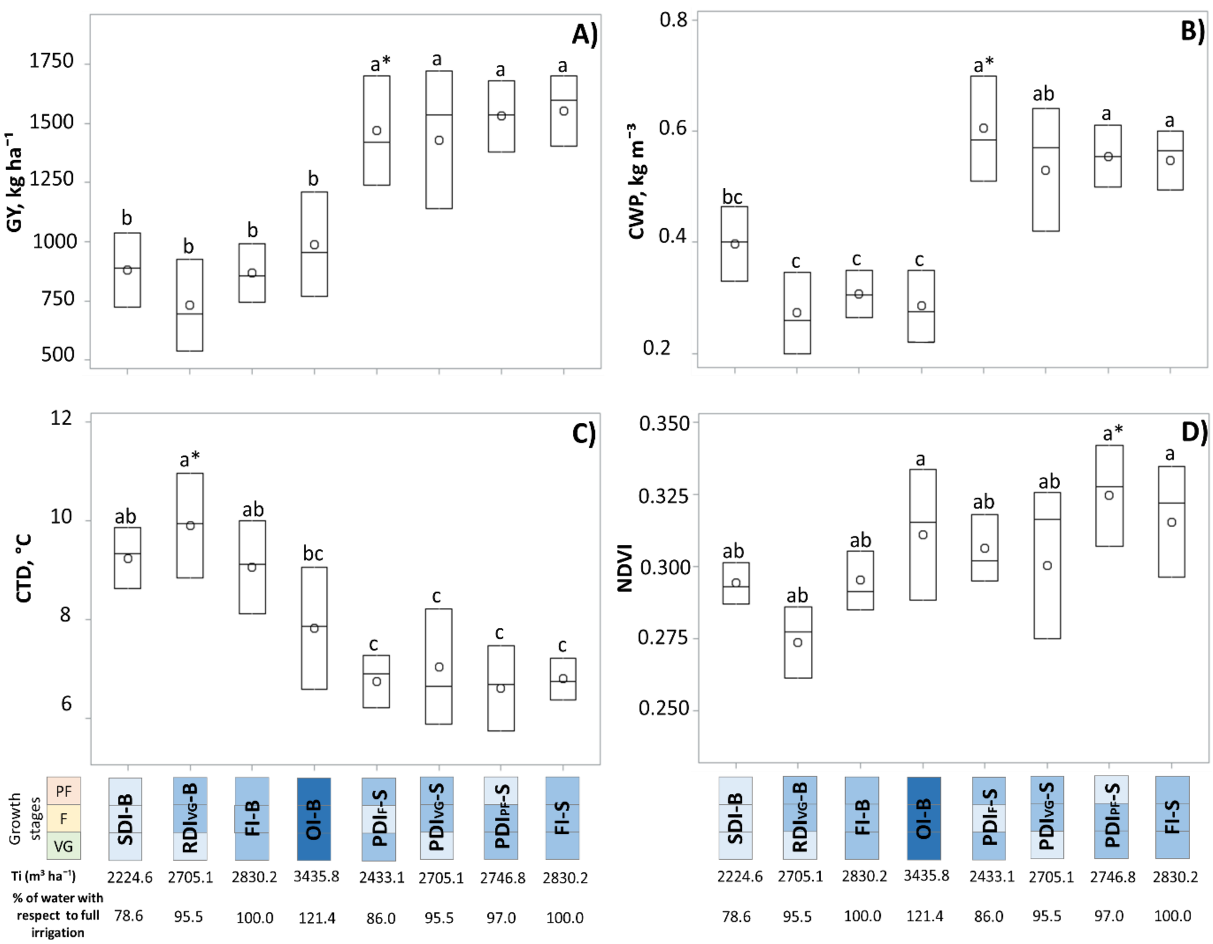

Figure 10. Box plot of A) grain yield (GY), B) crop water productivity (CWP), C) canopy temperature depression (CTD), and D) Normalized difference vegetation index (NDVI) in different treatments (combination of irrigation strategies and plant´s spatial arrangement) applied to chickpea crops during 2022. [abcd] Different letter among treatments indicates statistical significance ($p \leq 0.05$, LSD). VG= vegetative growth, F= flowering, PF= pod-filling. PDI= Partial root-zone drying irrigation. Dark, middle and light blue indicate 125, 100, and 75 % of ETc applied in specific growth stages across treatments. SDI-B = Sustained deficit irrigation + bed system with a double-row of plants. RDI_{VG}-B = Regulated deficit irrigation applied in VG stage + bed system with a double-row of plants. FI-B = Full irrigation applied during VG, F, and PF stages + bed system with a double-row of plants. OI-B= Over irrigation applied during VG, F, and PF stages + bed system with a double-row of plants. PDI_{F}-S = PDI applied during F stage + plants in a single-row. PDI_{VG}-S = PDI applied during VG stage + plants in a single-row. PDI_{PF}-S = PDI applied during PF stage + plants in a single-row. FI-S = Full irrigation applied during VG, F, and PF stages + plants in single row. Ti= Total irrigation applied for the crop.

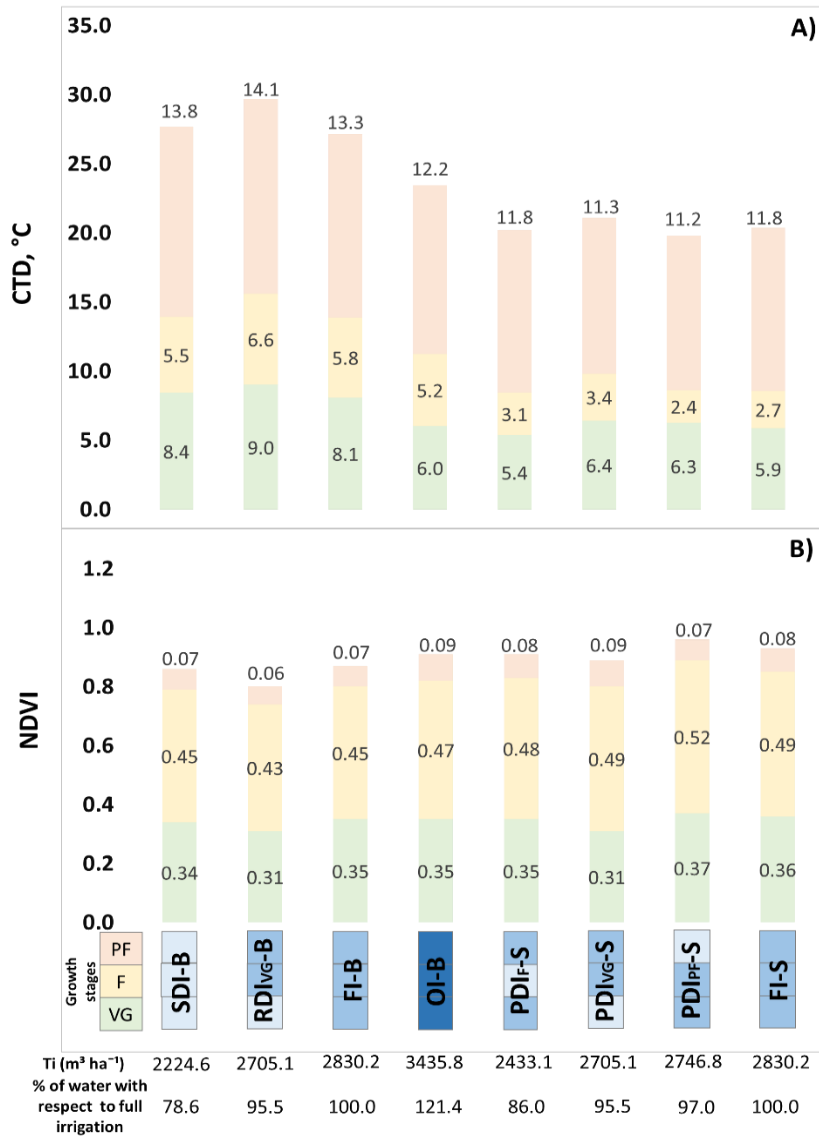

Figure 11. A) CTD and B) NDVI values accumulated and by growth stage for each irrigation treatments evaluated on chickpea crop. VG= vegetative growth, F= flowering, PF= pod-filling. PDI= Partial root-zone drying irrigation. Dark, middle and light blue indicate 125, 100 and 75 % of ETc applied in specific growth stages across treatments. SDI-B= Sustained deficit irrigation + bed system with a double row of plants. RDI_{VG}-B = Regulated deficit irrigation applied in VG stage + bed system with a double-row of plants. FI-B= Full irrigation applied during VG, F, and PF stages + bed system with a double-row of plants. OI-B= Over irrigation applied during VG, F, and PF stages + bed system with a double-row of plants. PDI_F-S = PDI applied during F stage + plants in a single-row. PDI_{VG}-S = PDI applied during VG stage + plants in a single-row. PDI_{PF} = PDI applied during PF stage + plants in a single-row. FI-S = Full irrigation applied during VG, F, and PF stages + plants in single row. Ti= Total irrigation applied for the crop.

3.4.2. Regression models for grain yield and crop water productivity with CTD and NDVI

NDVI (Figure 12A, 12B) and CTD (Figure 12C, 12D) mean values of irrigation treatments were positively and negatively related to GY and CWP, including all treatments. Likewise, a higher grain yield favors water productivity in chickpea cultivation (Figure 12E). A negative relationship between CTD and NDVI was also found (Figure 12F).

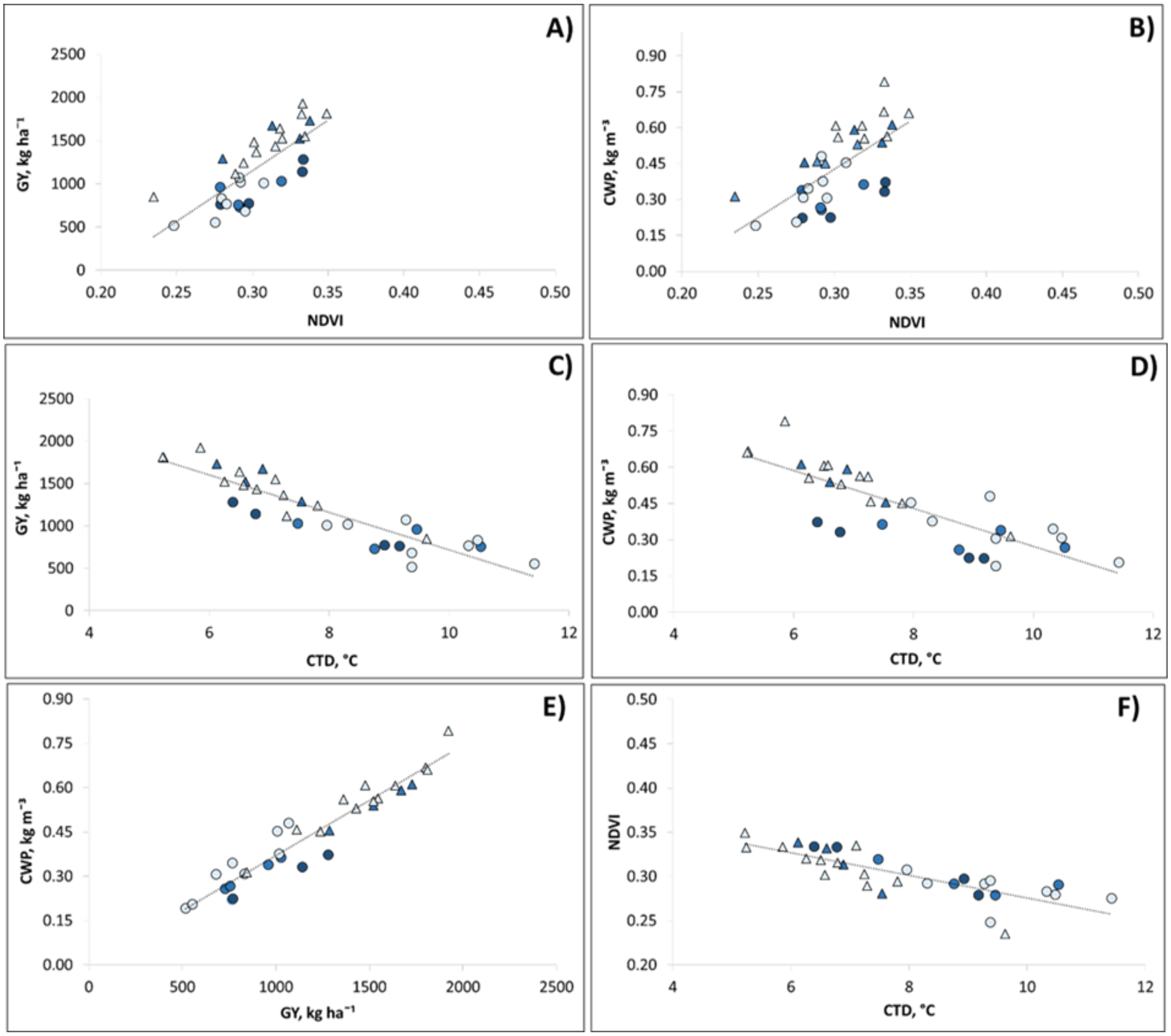

Figure 12. Grain yield (GY) and crop water productivity (CWP) are influenced by the value of normalized difference vegetation index (A and B, respectively) and canopy temperature depression (C and D, respectively) in accordance of difference irrigation treatments. E) Relationship between crop water productivity (CWP) and grain yield (GY), and F) Relationship between normalized difference vegetation index (NDVI) and canopy temperature depression (CTD) in chickpea cultivar, at the Todos Santos Experimental Station (INIFAP, Mexico). Circles correspond to bed-system and triangles to the single-row system. Dark, middle, and light blue indicate 125, 100 and 75 % of ETc applied in the specific growth stages considered in each treatment. Regression models: Figure 12A) GY= -2365.7 + 11720 NDVI, R^2= 0.59; Figure 12B) CWP= -0.7826 + 4.0308 NDVI, R^2= 0.46; Figure 12C) GY= 2919.3 – 220.02 CTD, R^2=0.81; Figure 12D) CWP= 1.0551 - 0.0782 CTD, R^2= 0.67; Figure 12E) CWP= -0.0031 + 0.0004 GY, R^2=0.91; Figure 12F) NDVI= 0.404 – 0.0128 CTD, R^2=0.63. All the regression models presented statistical significance $p \leq 0.01$.

Additionally, it was possible to generate prediction models of GY and CWP utilizing NDVI and CTD values by phenological stage and plant arrangement (Figure 18 and Figure 19 in Supplementary 2). Unlike the models in Figure 12, these last models showed a different coefficient of determination. In this respect, NDVI values predicted (Figure 18 in Supplementary 2) in a better way the GY values in of the irrigation treatment established in a single-row system with R^2 values between 0.32 and 0.72 (Figure 18B, 18D, 18F) while bed-system presented lower values (between 0.31 and 0.52; Figure 18A, 18C, 18E). In complement, the coefficient of determination values was higher for models that estimated GY at the flowering stage with R^2 =0.52 and R^2=0.72, respectively, for irrigation treatments established under bed-system and single-row (Figure 18C and 18D).

Models that predict GY with CTD utilization (Figure 19 in supplementary 2) presented coefficient of determination values between 0.27 and 0.81. The R^2 values were practically the same in both plant arrangements inside each crop growth stage; this is, R^2=0.27 at vegetative growth (Figure 19A and 19B), R^2 between 0.79 and 0.81 at flowering (Figure 19C and 19D), and R^2=0.52 at pod-filling stage (Figure 19E and 19F); we could appreciate that R^2 values were higher at flowering stage.

3.4.3. Classification of treatments by principal component technique and cluster analysis.

Data were summarized via principal component analysis (Table 12). The first two components (PC1 and PC2) accounted for 96.0% of the total variance, PC1 accounting for 70.5%. PC1 is a component related to grain yield, crop water productivity, and plant vigor and is negatively associated with canopy temperature depression; it is based on correlation values (r ≥ 0. 86) and statistical significance ($p \leq 0.01$), as shown in Table 12. On the other hand, PC2 explained 25.5% of the variance and was positively related to total irrigation (r ≥ 0. 86, $p \leq 0.01$; Table 12).

Figure 13A shows the distribution of the irrigation treatments in the first two principal components, while the cluster analysis (Figure 13B) helped to visualize the conformation of irrigation treatment groups.

The treatments that implemented the partial root-zone drying irrigation with the system of single-row of plants achieved the same level of plant vigor that allowed the highest production of grain (GY), crop water productivity (CWP) and provided a better water status and also lower values of canopy temperature depression values (CTD).

Table 12. Pearson correlation coefficients and Eigenvectors of every variable with the two principal component resultants.

Variable	Principal components PC1 r	PC1 Eigenvector	PC2 r	PC2 Eigenvector
GY	0.98**	0.524	-0.06	-0.060
CWP	0.91**	0.488	-0.39	-0.345
CTD	-0.98**	-0.522	-0.13	-0.123
NDVI	0.86**	0.462	0.35	0.311
Ti	-0.01	-0.009	0.98**	0.874
Eigenvalue	3.527		1.277	
Proportion (%)	70.50		25.50	
Cumulative (%)	70.50		96.00	

** $p \leq 0.01$. PC1 and PC2= Principal component 1 and 2, respectively. GY= Grain yield. CWP= Crop water productivity. CTD= Canopy temperature depression. NDVI= Normalized difference vegetation index. Ti= Total irrigation for crop.

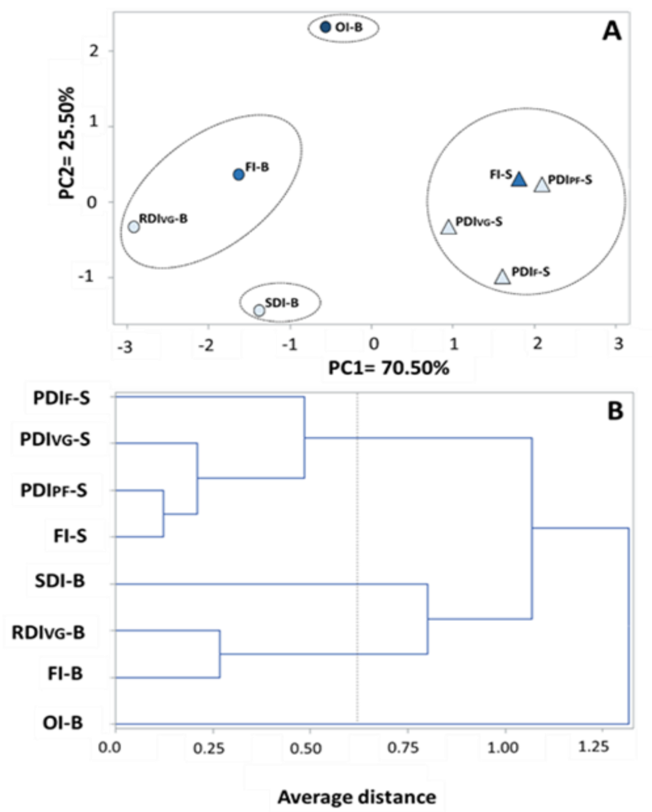

Figure 13. A) Principal components and B) Cluster analysis. VG= vegetative growth, F= flowering, PF= pod-filling. PDI= Partial root-zone drying irrigation. OI-B= Over irrigation applied during VG, F, and PF stages + bed system with a double-row of plants FI-B= Full irrigation + bed system with double row of plants. RDI_{VG}-B= Regulated deficit irrigation applied in VG stage + bed system with double row of plants. SDI-B= Sustained deficit irrigation + bed system with double row of plants. FI-S= Full irrigation + plants in single row. PDI_{VG}-S= drying irrigation applied during VG stage + plants in single row. PDI_{F}-S= Partial root zone drying irrigation applied during F stage + plants in single row. PDI_{PF}-S= Partial root zone drying irrigation applied during PF stage + plants in single row.). In Figure 13A, circles correspond to bed-system and triangles to the single-row system; dark, middle, and light blue indicate 125, 100 and 75 % of ETc applied in the specific growth stages considered in each treatment.

3.5. Discussion

3.5.1. CTD surpasses NDVI in efficiency to predict productivity under deficit irrigations strategies and plant spatial arrangement

Several studies have demonstrated the usefulness of the canopy temperature depression index (CTD) and the Normalized Difference Vegetation Index (NDVI) in determining crop yield and water productivity (Nemeskéri et al., 2018; Hou et al., 2019: Neupane, 2020; De Santis et al., 2022). However, few efforts have been undertaken to evaluate water-saving strategies, such as partial root-zone drying irrigation (PDI), regulated deficit irrigation (RDI), and sustained deficit irrigation (SDI) using remote information. In this sense, our results indicated that both the CTD and the NDVI (Figure 11) detected the variations imposed by the different irrigation treatments (over-irrigation, full irrigation, and deficit irrigation like PDI, RDI, and SDI) in the two plants spatial arrangement (bed-system and single-row).

The CTD had better predictive capabilities. The highest irrigation treatments had lower CTD values (Figure 10C); likewise, the single-row system treatments led to lower CTD values than those that used the bed system. Additionally, grain yield (GY, Figure 10A) and crop water productivity (CWP, Figure 10B) presented lower values in treatments with higher CTD. This behavior is consistent with the results found by Kumar et al. (2017) and Hou et al. (2019), who found that the increase in CTD was associated with the reduction of grain yield in crops such as soybeans (*Glycine max* L.), where for each degree Celsius the yield was reduced from 273 to 304 kg ha^{-1} of grain. In our work, each increase in one Celsius degree in CTD generated a loss of 220 kg ha^{-1} in GY (Figure 12C) and a reduction of 0.078 kg m^{-3} in CWP (Figure 12D).

Deficit irrigation treatments also led to lower NDVI values (Figure 10D); this trend was more remarkable in those established under bed system plant arrangements, which also had lower values of GY (Figure 10A) and CWP (Figure 10B). When plants grow under a water deficit, their leaves reflect less near-infrared and red irradiation, which causes lower NDVI values (Marín et al., 2020; Solgi et al., 2023). This behavior is consistent across various crops (Grados et al., 2020; Tavares et al., 2022).

CTD increased, and NDVI decreased from using bed-systems concerning single-row systems; this might be due to the distance from the plant to the drip tape (plant 0.2 m from both sides of the drip tape), turn less efficient the access of the roots to irrigation water, as has been found in other crops under drip irrigation conditions (Firouzabadi et al., 2021; Samoy-Pascual et al., 2022). However, the plant's proximity to the drip tape increases the material cost per surface unit (Firouzabadi et al., 2021; Samoy-Pascual et al., 2022). In our dataset, the deficit irrigation strategies using the partial root-zone drying irrigation resulted in larger GY and higher CWP, which agrees with previous reports (Iqbal et al., 2020), indicating that this technique is more efficient in providing plant water without diminishing crop yields.

3.5.2. Comparison of the multispectral or thermal imagery to predict grain yield and crop water productivity

Based on our general regression models, both GY and CWP were suitable to be estimated from NDVI (Figure 12A and 12B) and CTD (12C and 12D); however, the confidence of the models, as based on the values of R^2, were higher for CTD (R^2= 0.81 and 0.67 for the estimation of GY and CWP, respectively), in comparison to NDVI (0.59 and 0.46 for the estimation of GY and CWP, respectively). In this sense, although we found a positive relationship (R^2=0.91) between GY and CWP (Figure 12E) and from these with both remote metrics, we suggest implementing both the CTD and NDVI as crucial tools to predict GY and CWP in legumes. NDVI may indicate the magnitude of the leaf water stress, which could lead to crop management adjustments (Dong et al., 2020), while CTD would serve as a proxy for plant productivity (Kumar et al., 2017; Hou et al., 2019).

Periodic measurements can also help to direct water irrigation regimes in semi-arid areas (Coirini & Nolasco, 2016; Kumar et al., 2017; Hou et al., 2019; Rodocaj et al., 2023).

3.5.3. Timing for recording remotely sensed information is dependent on phenology

Our results show that crop phenology induces variations in the magnitude of CTD and NDVI (Figures 11A and 11B). Therefore, when considering the feasibility of performing flights to apply precision agriculture surveys, producers should be cautious of the specific moment of the life cycle of the specific crop. Given that both indices are influenced by phenology, they can additionally be associated with the timing of year and phenology and not only be utilized for irrigation management purposes, which is consistent with recommendations by Choudhary et al. (2019) and Neupane et al. (2020).

On the other hand, regression models utilizing CTD and NDVI for GY prediction were generated by the plant's spatial arrangement and by phenological stage, resulting in a final flowering model with higher R^2

values to estimate GY (Figure 18C and 18D, and 19C and 19D, both in Supplementary 2). Nemeskéri et al. (2018) also found that this index was closely related to grain yield when evaluating NDVI in snap beans (*Phaseolus vulgaris* L.), presenting the highest NDVI values when measured during flowering or capsule development.

3.6. Conclusions

Both UAV remotely sensed Canopy Temperature Depression (CTD) and Normalized Difference Vegetation Index (NDVI) can be used as a key tool to predict grain yield and crop water productivity in chickpeas. NDVI had no statistical significance to discriminate across treatments; however, it can still predict CWP and GY, although in a less precise fashion than CTD.

The best grain yield (1429.9 to 1552.4 kg ha^{-1}) and water productivity (0.53 to 0.60 kg m^{-3}) were obtained in those treatments that considered the partial root-zone drying irrigation strategy in the simple row plant arrangement. This combination could save between 85 and 396 m^3 ha^{-1}. The end of the flowering stage was the best time in phenology to predict grain yield.

We recommend expanding the evaluation of these indices in different crops, employing additional plant response variables, such as plant growth, health status, and water stress, to optimize crop productivity and its application in precision agriculture schemes.

Chapter 4. Integrated analysis of experiments (deficit irrigation implementation)

4.1. Abstract

Deficit irrigation is a valuable water-saving strategy in agriculture, increasing crop water productivity in scenarios of limited available freshwater. To evaluate the possible benefits of implementation of deficit irrigation strategies in chickpeas, we analyzed data on grain yield (GY), crop water productivity (CWP), plant height (H), plant dry weight (PDW), number of pods (PP), grains per plant (GP), grain caliber (Cal), and harvest index (HI) from three experiments developed in years 2020, 2021 and 2022 under drip tape irrigation. Test treatments included varying levels of regulated deficit irrigation, sustained deficit irrigation, partial root-zone drying irrigation, and the comparison with full and over-full irrigation. The total volume of water utilized in these treatments, denominated total irrigation (T_i), is between 884.48 and 3435.8 m^3 ha^{-1}. The relationship between dependent variables and T_i was determined through regression analysis. In addition, groups of irrigation treatments were formed and characterized using principal component and cluster analysis with the SAS software ver 9.3. The results showed a positive relationship between T_i and GY, PDW, PP, GP and H ($p< 0.01$), while Cal was less influenced ($p < 0.05$). CWP and HI showed a negative relationship with the increase in T_i ($p< 0.01$). The principal component and cluster analysis highlighted Group 1 as the outstanding irrigation treatments that included full irrigation (FI-S), partial root zone drying irrigation applied in vegetative growth (PDI_{VG}-S), flowering (PDI_F-S), and pod-filling stage (PDI_{PF}-S); this group presented mean values of 2611.3 m^3 ha^{-1} in T_i, 1495.5 kg ha^{-1} of GY, 17.2 g in PDW, 0.5 m in H, 14.1 in GP, 11.9 in PP, CWP of 0.56 kg m^3 and HI of 0.42. Inside Group 1, utilizing PDI_F-S resulted in a good option considering the water-saving (397.09 m^3 ha^{-1}, *i.e.*, 14 less water) about full irrigation. The evaluation confirmed the benefit of implementing deficit irrigation strategies as a water-saving alternative in chickpea production without affecting grain yield and contributing to increased CWP.

4.2. Introduction

This chapter has been realized to analyze together the response of the chickpea crop concerning 24 irrigation treatments described in chapters 2 (experiments years 2020 and 2021) and 3 (experiment year 2022). The first approach of this analysis was directed to describe the variables (Table 13) tendency in response to total irrigation (T_i in m^3 ha^{-1}) intra and inter year; T_i is the total water that chickpea crop received in its life cycle on each treatment. The second approach was to generate groups of irrigation treatments by their similarity and characterize them, considering the grain yield, crop water productivity, and other plant characteristics (Table 13). Finally, for each group conformed, we estimated the potential energy cost saved as another benefit of implementing deficit irrigation strategies.

4.3. Materials and methods

To accomplish the first approach, we utilized all the observations (n=96) of each variable mentioned in Table 13 corresponding to each irrigation treatment tested. In contrast, for the second one, we used the average response of each treatment. For more details on the variables in Table 13, refer to sections 2.1.5 and 3.3.3.

Ti had values of 884.48 and 3435.80 m^3 ha^{-1} (Table 14). It is important to note that the variation in the volumes of Ti in the experiment developed during the same period (December-April) of the three years tested (2020, 2021, and 2022) resulted from the reference evapotranspiration estimated throughout the phenology of the crop and adjusted by crop coefficients specific for each stage of development and the percent of crop evapotranspiration implemented associated to each irrigation treatment established (Table 4 section 2.1.4 and Table 20 in Supplementary 2).

We applied a regression analysis to learn about the tendency between response variables and the increase in intra- and inter-annual T_i. We used principal components and cluster analysis for the conformation and characterization of groups of irrigation treatments.

Table 13. Chickpea variables were utilized to determine the influence of total irrigation (T_i) and identify the outstanding irrigation treatment for crop yield and water productivity.

Variable	Symbol	Unit
Grain yield	GY	kg ha^{-1}
Grain caliber	Cal	grains in 30 g
Plant height	H	m
Plant dry weight	PDW	g $plant^{-1}$
Number of pods per plant	PP	-
Number of grains per plant	GP	-
Harvest index	HI	-
Crop water productivity	CWP	kg m^{-3}

An energy cost was determined for each irrigation treatment group conformed; this linked to the corresponding volume of water considered. The cost per m^3 of irrigation water was determined based on the monthly record of water volumes utilized and the energy cost implicated in the extraction and repumping during the period that the experiment was established at the INIFAP´s Todos Santos Experimental Station (Table 15).

Table 14. General description of irrigation treatments evaluated in three years at INIFAP's Todos Santos Experimental Station in Baja California Sur, Mexico.

Year	**General treatments description***	**Range of T_i m^3 ha^{-1}**
2020	Full irrigation, regulated deficit irrigation applied in vegetative, flowering and pod-filling stages and sustained deficit irrigation strategies	884.48 to 1006.78
2021	Full irrigation, regulated deficit irrigation applied in vegetative, flowering and pod-filling stages and sustained deficit irrigation strategies	1320.88 to 1497.54
2022	Over full irrigation, full irrigation, regulated deficit irrigation, sustained deficit irrigation in bed system and partial root zone drying irrigation in single line system	2224.66 to 3435.80

T_i= Total irrigation. *For more detail about irrigation treatment check Table 4 section 2.1.4 and Table 20 in Supplementary 2.

Table 15. Cost of water ($ Mexican m^{-3}) at the Todos Santos Experimental Station

Characteristics	Year of evaluation		
	2020 January-April	2021 January-April	2022 January-April
Total water volume extracted in the experimental station m^3	935.3	1576.24	1609.17
Energy consumed by the irrigation system kWh	1389.00	2286.00	2311.00
Energy cost* $ kWh	0.64	0.66	0.68
Low tension and power factor cost ($)	37.08	83.25	102.06
Energy service cost $ kWh^{-1}	926.04	1592.01	1673.54
Cost of water $ m^{-3}	0.99	1.01	1.04

*Tariff is defined by Mexican Federal Electricity Commission by month and year. 9N scheme (energy for agriculture irrigation) was applied for the energy service cost at Todos Santos Experimental Station. The information could be consulted at: https://app.cfe.mx/Aplicaciones/CCFE/Tarifas/TarifasCRENegocio/Negocio.aspx. Note: Water consumption in each period of the year at the experimental station differs from the total irrigation applied in each irrigation treatment because the last ones were an extrapolation of water volumes involved in each experimental plot.

4.4. Results

4.4.1. Variables tendency in response to total irrigation

The inter-annual response of eight variables to the increase in total irrigation is shown in each item in Figure 14. At the lower right corner of each item in Figure 14 appear the R^2 values for every polynomial relationship (R^2 between 0.08 and 0.46); they all presented low values but with statistical significance ($p < 0.05$ or $p < 0.01$). In this sense, increased total irrigation favorably influences grain yield (Figure 14A), plant dry weight (Figure 14B), plant height (Figure 14C), grain caliber (Figure 14D), grain per plant (Figure 14E), and pods per plant (Figure 14F). Besides, increases in total irrigation reduce crop water productivity (Figure 14G) and harvest index (Figure 14A).

For intra-annual analysis, only grain yield in years 2020 (Figure 14A; model with R^2= 0.26, $p < 0.05$) and 2021 (Figure 14A; model with R^2= 0.29, $p < 0.01$), plant dry weight in the year 2021 (Figure 14 B; model with R^2= 0.26, $p < 0.05$), plant height in the year 2020 (Figure 14 C; model with R^2= 0.42, $p < 0.01$), grain per plant in the year 2021 (Figure 14 E; model with R^2= 0.31, $p < 0.01$), pod per plant in the year 2021 (Figure 14 F; model with R^2= 0.31, $p < 0.01$) and harvest index in the year 2022 (Figure 14 H; model with R^2= 0.51, $p < 0.01$) presented a relationship with the total irrigation levels applied. The response of the previous variables to total irrigation, except for the harvest index, was favorable.

4.4.2. Characterization of irrigation treatments

The principal component analysis showed that the first three components (PC1, PC2, and PC3) were important (Eigenvalue> 1), explaining together 90.8% of the total variance (Table 16). Regarding the sense of each of the three main components, they were defined based on the variables with the highest weight inside them ($r \geq 0.70$ with $p \leq 0.01$, and Eigenvector ≥ 0.40) within each component (Table 16). Thus, component one (CP1) was positively related to total irrigation volume (r=0.78), grain yield (r=0.72), plant dry weight (r=0.91), grain (r= 0.94), and pods per plant (r=0.93). The principal component two (CP2) was related to crop water productivity (r=0.79) and harvest index (r=0.85). Finally, principal component 3 (CP3) was positively associated with grain caliber (r=0.73) (Table 16).

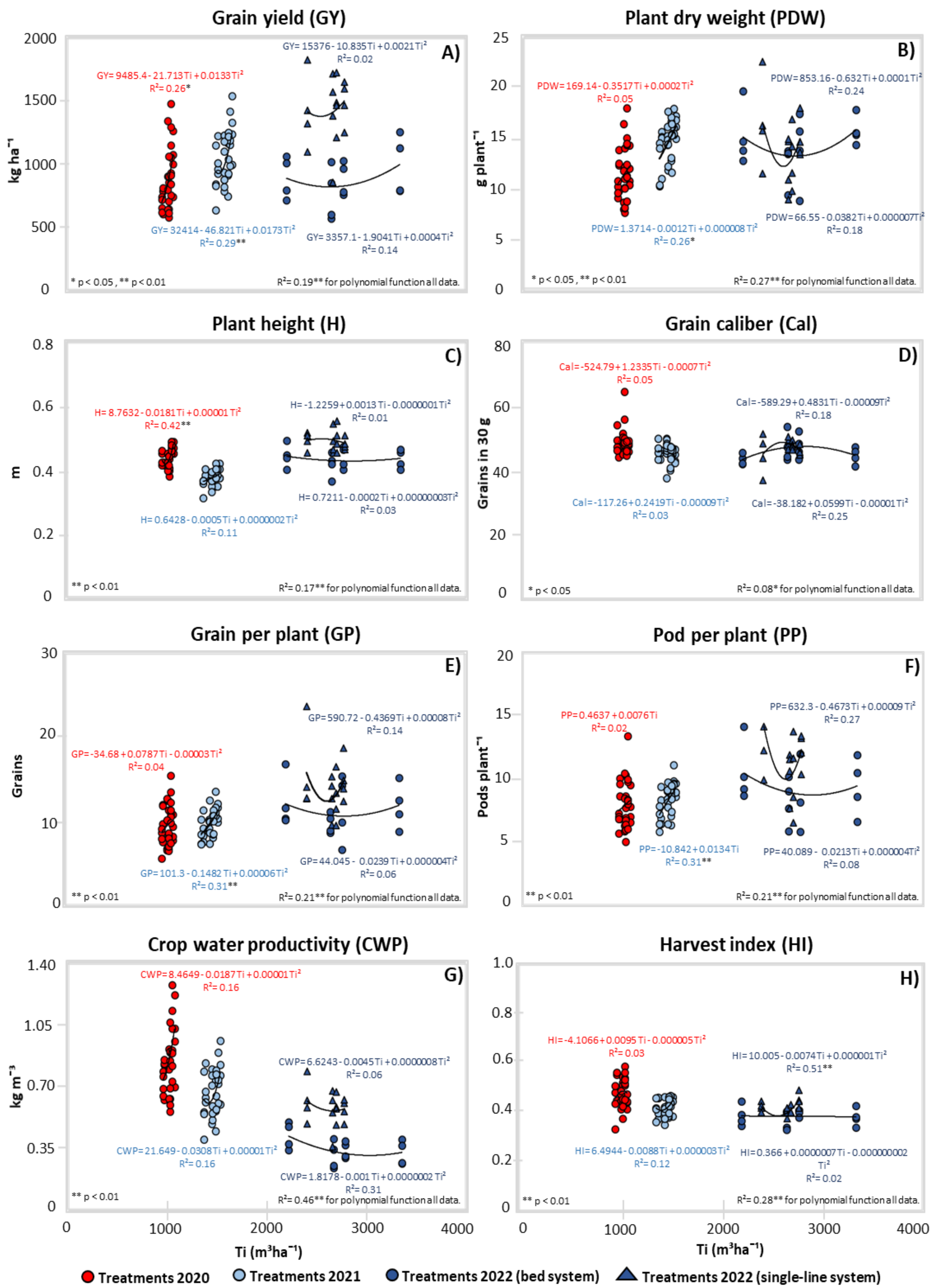

Figure 14. Influence of increasing total irrigation (T_i) of chickpea crop on: A) Grain yield. B) Plant dry weight. C) Plant height. D) Grain caliber. E) Grains per plant. F) Pods per plant. G) Crop water productivity. H) Harvest index.

Table 16. Pearson´s correlation coefficients (r) and Eigenvectors of every variable with the three principal component resultants.

Variable	Principal components					
	PC1		PC2		PC3	
	r	Eigenvector	r	Eigenvector	r	Eigenvector
T_i	0.78**	0.36	-0.43	-0.29	0.36	0.30
GY	0.77**	0.35	0.38	0.26	0.23	0.19
PDW	0.91**	0.42	0.01	0.01	-0.35	-0.30
H	0.39	0.18	0.51**	0.35	0.67**	0.56
Cal	-0.60**	-0.27	0.11	0.07	0.72**	0.61
GPP	0.94**	0.43	0.28	0.19	-0.03	-0.02
PP	0.93**	0.43	0.25	0.17	-0.06	-0.05
CWP	-0.52**	-0.24	0.79**	0.54	-0.09	-008
HI	-0.22	-0.10	0.85**	0.58	-0.29	-0.24
Eigenvalue	4.6		2.1		1.3	
Proportion (%)	51.8		23.5		15.5	
Cumulative (%)	51.8		75.3		90.8	

** $p \leq 0.01$. Variable selection criteria inside each principal component: r ≥ 0.70 with $p \leq 0.01$, and Eigenvector ≥ 0.35. T_i= Total irrigation. H=plant height. PDW= plant dry weight. PP=pod per plant. Cal= grain caliber. GY= grain yield. CWP= crop water productivity. HI= harvest index. GP= grain per plant.

Figure 15A shows the distribution of all irrigation treatments in the first three principal components, while the cluster analysis (Figure 15B) helped to the conformation of irrigation treatment groups.

Group 1 was integrated by treatments that implemented full irrigation (FI-S), partial root-zone drying irrigation in vegetative growth (PDI_{VG}-S), flowering (PDI_F-S), and pod-filling stage (PDI_{PF}-S) with plant arrangement of single-rows established in the year 2022.

Group 1 presented the higher values of grain yield (1495.5 kg ha^{-1}, Figure 16A), plant dry weight (17.2 g, Figure 16B) and height (0.5 m, Figure 16C), grain (14.1, Figure 16E) and pods (11.9, Figure 16F) per plant; crop water productivity and harvest index in this group were 0.56 kg of grain m^{-3} (Figure 16G) and 0.42 (Figure 16H), respectively.

As cluster analysis considered equal to the irrigation treatments inside Group 1, then utilizing PDI_F-S could implicate the best options considering the water-saving because this treatment utilized 397.09 m^3 ha^{-1} less water (14.1% of water saved) concerning full irrigation (Table 20 in Supplementary 2); moreover, PDI_{VG}-S and PDI_{PF}-S implicated the reduction in 125 and 83.4 m^3 ha^{-1}, *i.e.*, 4.5 and 3.0 % of water saved, respectively, about FI-S (Table 20 in supplementary 2).

Group 2 was integrated by irrigation treatments of full irrigation (FI-B), regulated deficit irrigation implemented in vegetative growth (RDI_{VG}-B), and sustained deficit irrigation (SDI-B) established with plant arrangement of bed system in the year 2022. This group presented values of 826.8 kg ha^{-1} of grain yield (Figure 16A), 14.2 g in plant dry weight (Figure 16B), 0.44 m in plant height (Figure 16C), 46.6 grains in 30 g sample as grain caliber (Figure 16D), 10.6 grains per plant (Figure 16E), 9.3 pods per plant (Figure 16F), 0.33 kg m^{-3} in crop water productivity (Figure 16G), and 0.37 in harvest index (Figure 16H).

Inside Group 2 of treatments, implementing SDI-B and RDI_{VG}-B implicate advantages of saving 605.6 and 125.1 m^3 ha^{-1} about FI-B, *i.e.*, 21.4 and 5.5 % less water, respectively.

Group 3 was integrated by the irrigation treatment of over-irrigation (OI-B) established with plant arrangement of bed system in 2022.

The characteristics of group 3 were 989.2 kg ha^{-1} of grain yield (Figure 19 A), 16.3 g of plant dry weight (Figure 19B), 0.44 m of plant height (Figure 19C), 45.1 grains in 30 g sample of caliber (Figure 19D), 11.4 grains per plant (Figure 19E), 9.3 pod per plant (Figure 19F), 0.29 kg m^{-3} of crop water productivity (Figure 19G) and 0.37 of harvest index (Figure 19H).OI-B was considered as an irrigation treatment to explore a higher level of total irrigation about FI-B established in the year 2022 (605.2 m^3 ha^{-1}, *i.e.*, 21.3%) to know the response in GY and CWP in chickpea crop under bed-system, but, even though the value of GY was increased concerning the treatments included in Group 2 (826.8 *versus* 989.2 kg ha^{-1}), but did not improve crop water productivity (0.33 vs 0.29 kg m^{-3}).

Finally, Group 4 was constituted by all the irrigation treatments (FI, VG_{50}, VG_{75}, F_{50}, F_{75}, PF_{50}, PF_{75}, and SDI) established in 2020 and 2021 years under plant arrangement of bed system. The average values were 909.7 kg ha^{-1} in grain yield (Figure 19A), 12.8 g like plant dry weight (Figure 19B), 0.42 m plant height (Figure 19B), 48.3 grains in 30 g sample like grain caliber (Figure 19B), 9.2 grains per plant (Figure 19E), 7.8 pods per plant (Figure 19F), 0.81 kg m^{-3} in crop water productivity (Figure 19G), and 0.44 as harvest index (Figure 19H).

For the implications described in section 2.2.1. and 2.2.4., the VG_{75} irrigation treatment stands out in this group, which generated higher grain yield (Table 6 in section 2.4.2.) and water productivity (Table 8 in section 2.2.4.) about FI; VG_{75} saved an average of 24 m^3 ha^{-1} in the two years of evaluation.

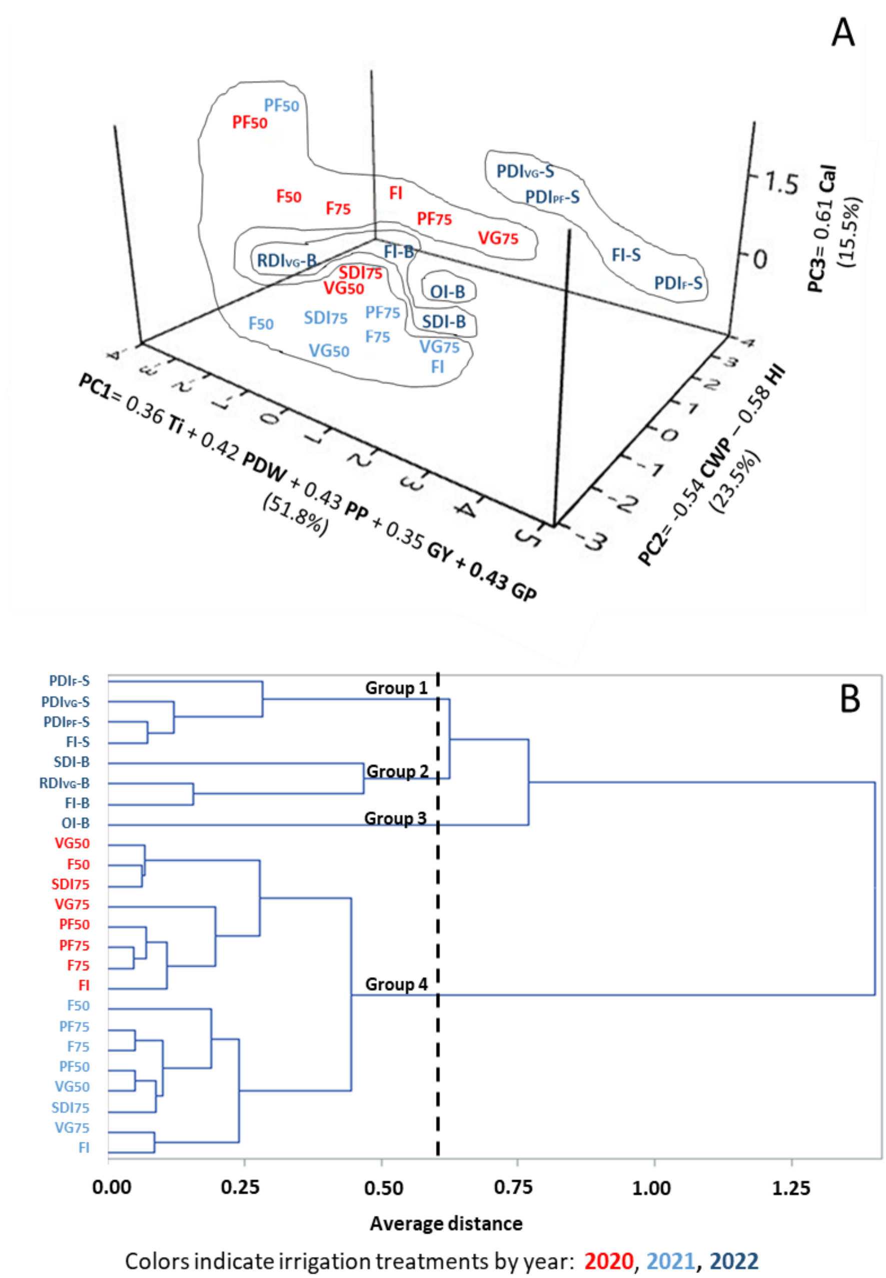

Figure 15. **A**) Distribution of all irrigation treatments in the first three principal components. **B**) Conformation of groups of irrigation treatments through cluster analysis. Vegetative growth (VG), flowering (F), and pod-filling (PF) stages. ETc= Crop evapotranspiration. Description of irrigation treatments evaluated in 2020 and 2021: RDI = regulated deficit irrigation. FI = full irrigation application of 100% ETc during VG, F, and PF. SDI_{75} = sustained deficit irrigation applying 75% of ETc during VG, F, and PF. VG_{50} = RDI applying irrigation equivalent to 50% of ETc in VG. VG_{75} = RDI applying irrigation equivalent to 75% of ETc in VG. F_{50} = RDI applying irrigation equivalent to 50% of ETc in F. F_{75} = RDI applying irrigation equivalent to 75% of ETc in F. PF_{50} = RDI applying irrigation equivalent to 50% of ETc in PF. PF_{75} = RDI applying irrigation equivalent to 50% of ETc in PF. Description of irrigation treatments evaluated in the year 2022. PDI= Partial root-zone drying irrigation. OI-B= Over irrigation applied during VG, F, and PF stages + bed-system with a double-row of plants. FI-B= Full irrigation + bed-system with a double row of plants. RDI_{VG}-B= Regulated deficit irrigation applied in VG stage + bed-system with a double row of plants. SDI-B= Sustained deficit irrigation + bed system with a double row of plants. FI-S= Full irrigation + plants in single-row. PDI_{VG}-S= Partial root-zone drying irrigation applied during VG stage + plants in single-row. PDI_{F}-S= Partial root-zone drying irrigation applied during F stage + plants in single-row. PDI_{PF}-S= Partial root-zone drying irrigation applied during PF stage + plants in single-row.

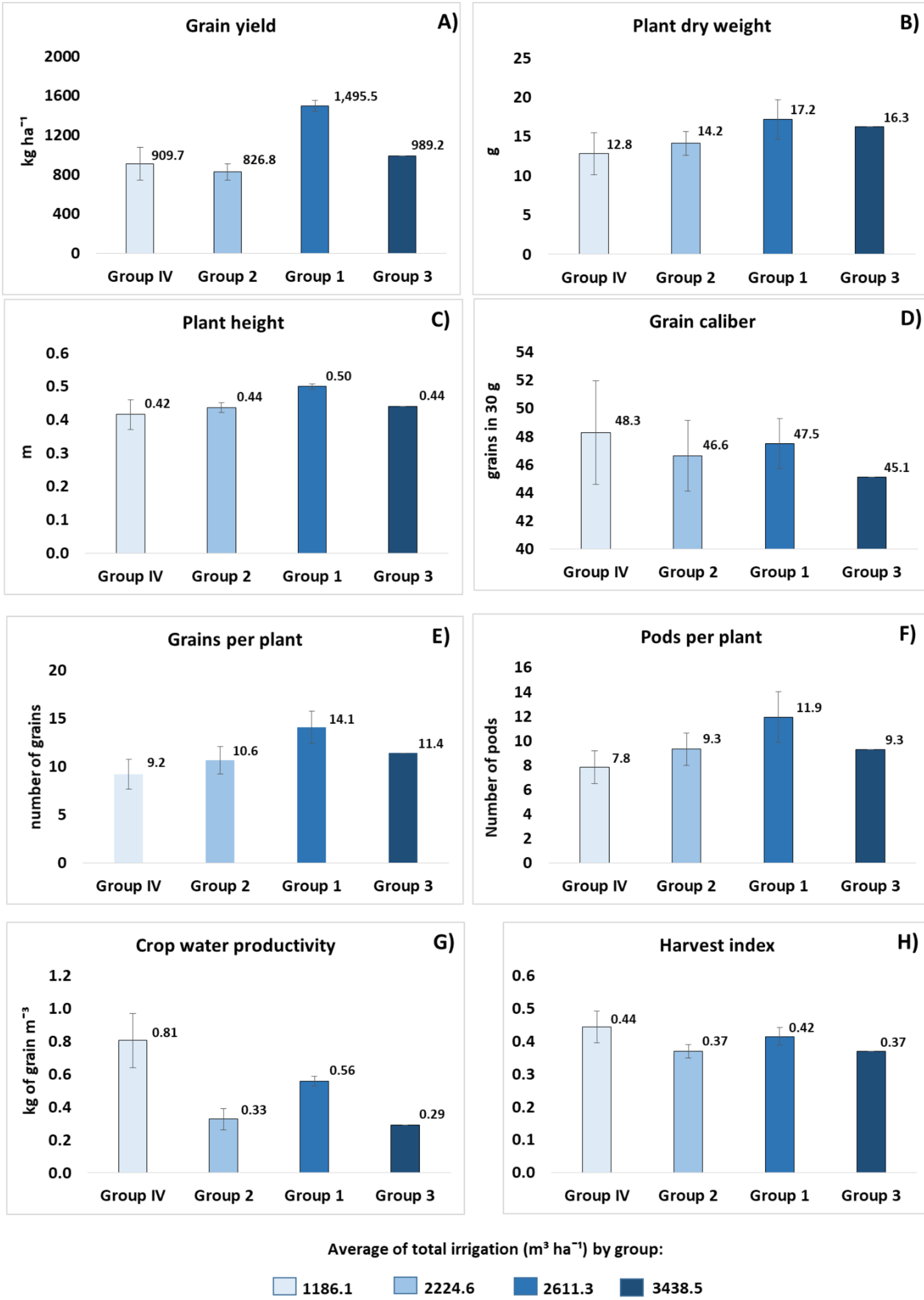

Figure 16. Average and standard deviation for different variables by group conformed by cluster analysis. A) Grain yield, B), Plant dry weight, C) Plant height, D) Grain caliber, E) Grains per plant, F) Pods per plant, G) Crop water productivity, and H) Harvest index.

4.4.3. Energy cost related to irrigation groups

Based on the estimated cost per unit of applied irrigation volume ($ m^{-3}) shown in Table 15, the energy cost of implementing total irrigation in each treatment and the average cost per group were estimated (Table 17).

Table 17. Average cost ($ ha^{-1}) by group of irrigation treatments.

Group	Irrigation treatment	Total irrigation	$ m³	Total cost $ ha^{-1}	Average cost by group ± SD $ ha^{-1}	V.C. %
1	FI-S	2830.2	1.04	2943.4	2786.0 ±154.8	5.5
	PDI_{PF}-S	2746.8	1.04	2856.6		
	PDI_{VG}-S	2705.2	1.04	2813.3		
	PDI_{F}-S	2433.2	1.04	2530.4		
2	SDI-B	2224.7	1.04	2313.6	2690.1 ± 271.4	10.0
	RDI_{VG}-B	2705.2	1.04	2813.3		
	FI-B	2830.2	1.04	2943.4		
3	OI-B	3435.8	1.04	3573.2	3573.2 ± 0.0	0.0
4	FI	1497.5	1.01	1512.5	1188.4 ± 250.4	21.0
	VG_{75}	1473.1	1.01	1487.8		
	PF_{75}	1454.5	1.01	1469.0		
	VG_{50}	1448.7	1.01	1463.1		
	PF_{50}	1411.3	1.01	1425.4		
	F_{75}	1409.2	1.01	1423.3		
	SDI_{75}	1342.0	1.01	1355.4		
	F_{50}	1320.9	1.01	1334.0		
	FI	1006.8	0.99	996.7		
	VG_{75}	983.4	0.99	973.5		
	PF_{75}	983.0	0.99	973.1		
	VG_{50}	960.2	0.99	950.5		
	PF_{50}	959.2	0.99	949.6		
	F_{75}	945.6	0.99	936.1		
	SDI_{75}	897.8	0.99	888.8		
	F_{50}	884.5	0.99	875.6		

Different colors indicate year when were treatments implemented and calculus generated: 2020, 2021 and 2022. V.C. = Variation coefficient by group of irrigations treatments. SD= Standard deviation. Vegetative growth (VG), flowering (F), and pod-filling (PF) stages. ETc= Crop evapotranspiration. PDI= Partial root-zone drying irrigation. Description of irrigation treatments evaluated in years 2020 and 2021: RDI = regulated deficit irrigation. FI = full irrigation application of 100% ETc during VG, F and PF. SDI_{75} = sustained deficit irrigation applying 75% of ETc during VG, F, and PF. VG_{50} = RDI applying irrigation equivalent to 50% of ETc in VG. VG_{75} = RDI applying irrigation equivalent to 75% of ETc in VG. F_{50} = RDI applying irrigation equivalent to 50% of ETc in F. F_{75} = RDI applying irrigation equivalent to 75% of ETc in F. PF_{50} = RDI applying irrigation equivalent to 50% of ETc in PF. PF_{75} = RDI applying irrigation equivalent to 50% of ETc in PF. Description of irrigation treatments evaluated in year 2022. OI-B= Over irrigation applied during VG, F, and PF stages + bed system with a double-row of plants FI-B= Full irrigation + bed system with double row of plants. RDI_{VG}-B= Regulated deficit irrigation applied in VG stage + bed system with double row of plants. SDI-B= Sustained deficit irrigation + bed system with double row of plants. FI-S= Full irrigation + plants in single row. PDI_{VG}-S= PDI applied during VG stage + plants in single row. PDI_{F}-S= PDI applied during F stage + plants in single row. PDI_{PF}-S= PDI applied during PF stage + plants in single row.

The average energy cost was 2786 ± 154.8, 2690 ± 271.4, 3573.2, and 1188.4 \$ ha^{-1} for groups 1, 2, 3, and 4, respectively (Table 17). It is observed that the variation in energy cost between treatments within groups varied between 5.5 and 21%.

4.5. Discussion

4.5.1. Variables tendency in response to total irrigation

The inter and intra-annual regression model presented low R^2 values (all models in Figure 14); this could have been generated by more variation produced for all irrigation treatments, year effect, and total irrigation level range considered in each year. As the relationship between dependent and independent variables is statistically significant, essential conclusions can still be drawn about the relationship between variables (MINITAB, 2014; Frost, 2024).

The inter-annual response of grain yield, plant dry weight, number of pods and grain per plant to the increase in total irrigation, this is a consistent response with the trends shown by Kumar et al. (2021) and Mhaske (2019). This consequent increase in yield has been attributed to a level of total irrigation that favored the needs of the plant to a greater degree, contributing to a better establishment, growth, and development, which results in an increase in the transfer of assimilated products to the reproductive organs, in addition to reducing flowers and pods abortion (Singh et al., 2016).

During 2022, higher total irrigation levels were applied than those implemented in 2020 and 2021, and even though the treatments that established deficit irrigation strategies in the single-row system presented yields with higher values (average grain yield of 1495 kg ha^{-1} for Group I Figure 16A) than those obtained in previous years (average of 909 kg ha^{-1} for Group IV Figure 16A), while deficient irrigation treatments in bed-system showed low yields (average of 826.8 kg ha^{-1} Figure 16A) even under over-full irrigation conditions (989.2 kg ha^{-1} for Group II Figure 16A). The limited productive response could be caused by high temperatures (above 33°C) presented during various moments in the 2022 growth cycle, but primordially during the flowering and pod-filling stage (Figure 17) compared with the temperatures presented during 2020 and 2021, where maximum temperatures were below 31°C (Figure 3). The high temperature could affect the percentage of germinated pollen, pod production, the number of seeds per pod, and the final crop yield. Similar impacts of drought on pollen production were found in other chickpea genotypes

(Sivakumar et al., 1987; Devassirvatham et al., 2012; Fierros et al., 2017).

For intra-annual regression models, in cases that resulted in a significative curvilinear relationship, several authors have pointed out that the legume production function shows a linear relationship with the level of irrigation. At the same time, they argued that the function could take a curvilinear form with the drop in yield linked to an excess of water that generates effects on the plant due to a waterlogging condition, lack of aeration in the root zone, nutrient washing, or the presence of diseases reported (Ray et al., 2023).

In this study, curvilinear responses can be attributed to implicit aspects inside the value of total irrigation (independent variable) considered for the regression analysis, *i.e*., the effects of deficit irrigation treatments, plant arrangements (bed vs single-row system), and year effects.

Concerning the variables, plant height, pod, and grains per plant are favored by the level of irrigation, while grain caliber is reduced. In this topic, Korbu et al. (2022), when evaluating the response of chickpeas to different moisture levels: no tress, mild stress, and severe stress under furrow irrigation in Ethiopian conditions found a decrease in plant height (0.48 to 0.38 m), 100 seed weights (31 to 27 g), and grain yield (2218 to 1650 kg ha^{-1}) linked to water diminishment; water restriction affected in a greater degree the number of pods (-29%) and the consequent number of grains, while the one hundred grain weight lost 13 % with respect no stress condition. In our study, considering the slope in the regression models (Figure 14), pod and grain per plant were more affected in reference to plant height and grain caliber.

The negative relationship found in crop water productivity agrees with reports by Singh et al. (2016), who mentioned that this variable should not be taken as an isolated indicator of the selection of outstanding irrigation treatments; this is caused by treatments with low irrigation or without complementary irrigation have exhibited higher crop water productivity; it has also been argued by Singh et al. (2016) that a linear increase in grain yield does not necessarily mean a higher CWP.

Concerning harvest index response, it is concordant with previous research reporting that the water deficit applied in reproductive stages increases the allocation of plant resources in the reproductive organs, improving the productivity parameters in the crop (Kang et al., 2008). Kumar et al. (2021) noted that the harvest index increased with irrigation restrictions generated.

4.5.2. Characterization of irrigation treatments

Principal components and cluster analysis generate irrigation treatment groups and their description. Group 1, which included the irrigation treatments established in the single-row system, i.e., full irrigation (FI-S) and partial root-zone drying irrigation applied during vegetative growth (PDI_{VG}-S), flowering (PDI_F-S) and pod-filling (PDI_{PF}-S). This group presented the highest values of grain yield, plant dry weight, grain, and pod per plant. It is essential to highlight that although this group did not present the highest value of water productivity, as indicated by Singh et al. (2016), this variable should not be considered an independent indicator of the selection of outstanding irrigation treatments.

As indicated in the results section, given that the four treatments were considered the same in their productive characteristics, the treatment (PDI_F-S) is considered outstanding, which is the one that used the lowest volume of water among this group and a slight value of water productivity. Thus, Zwart and Bastiaanssen (2004) pointed out that deficit irrigation can increase crop water productivity.

In the particular case of the use of irrigation with partial root-zone drying irrigation, which considers a restriction of irrigation in a specific stage of crop development in alternating irrigation events, it is generated that one part of the root system absorbs water and another remains dry; this condition generates the production of higher levels of abscisic acid in the xylem of the plants, this generates a partial closure of the stomata and a reduction in leaf expansion. In contrast, the irrigated roots fully absorb water to sustain an elevated water condition in the plant shoots (Iqbal et al., 2020). The benefits of implementing this technology have been reported in green beans (*Phaseolus vulgaris* L.) by Gencoglan et al. (2006).

4.5.3. Energy cost related to irrigation groups

Improving irrigation technologies and practices has been identified as one of the most important alternatives to reduce the effects of water scarcity (Ingrao et al., 2023). This chapter identified Group 1 of irrigation treatments as the outstanding group in productive aspects and middle in crop water productivity. The water savings between the most significant and lowest volume of water used by the treatments in this group resulted in 397 m^3 ha^{-1} (%14 less water; Table 20 in Supplementary 2), which implied a variation in energy cost of 5% (\$154.8 ha^{-1}) concerning the group´s average energy cost of \$2786 ha^{-1}. As can be seen, irrigation strategies and water saving can be an alternative for energy saving and reducing the environmental impact derived from the energy generation process. However, given the current electricity subsidy scheme (Ramo & Rivero, 2012; Peñalosa et al., 2021), this element can make technology transfer complex. However, it could undoubtedly be a way when the public energy subsidy policy is compromised.

4.6. Conclusion

Total irrigation positively influenced the grain yield and plant characteristics as dry weight, pod, and grain per plant, while height and grain caliber were less influenced. Harvest index and crop water productivity showed a negative relationship with the increase in total irrigation.

When very low irrigation treatment are tested, these exhibit higher crop water productivity; in this sense, the crop water productivity variable should not be taken as an isolated indicator of the selection of outstanding irrigation treatments.

Concerning deficit irrigation strategies, partial root-zone drying irrigation resulted in a better option than regulated or sustained deficit irrigation; inside partial root-zone drying irrigation strategy applied during the flowering stage led to a higher level of water-saving (397.09 m^3 ha^{-1}, *i.e.*, 14% less water compared with full irrigation) without significant grain yield loss, contributing to the increase in crop water productivity. This evaluation confirmed the benefit of implementing deficit irrigation strategies as a water-saving practice in chickpea production.

Chapter 5. General discussion

5.1. Regulated deficit irrigation during vegetative growth enhance crop water productivity in chickpea (*Cicer arietinum* L.)

The treatments that achieved higher grain yield were full irrigation or those that applied regulated deficit irrigation (RDI) considering crop evapotranspiration of 75% during the vegetative growth (VG_{75}), flowering (F_{75}), or pod filling (PF_{75}) stages; the latter three treatments saved 24, 74, and 34 m^3 ha^{-1} of water on average in the two years of evaluation of (the average of the two growing seasons; Table 4). Oppositely, the lowest grain yield was produced by treatments in the VG_{50}, F_{50}, and PF_{50} stages (Table 6). The results of grain yield under full irrigation and RDI during vegetative growth are consistent with those of other studies for the Desi chickpea, showing the best grain yield (6.7 t ha^{-1}) under irrigation restriction at the vegetative stages (50% ETc), followed by full irrigation treatment (4.9 t ha^{-1}) (Hirich et al., 2011) with irrigation volumes of 2300 m^3 ha^{-1} and 2750 m^3 ha^{-1}, respectively. Further evidence indicates that the grain yield performance under RDI was reduced concerning full irrigation, restricting grain yield by up to 38% (Sachdeva et al., 2022). In our study, grain yield from sustained deficit irrigation (SDI) treatment was better than for treatments in VG_{50}, F_{50}, and PF_{50}, as the latter treatments experienced a shorter period of stress but with a more intensive irrigation restriction (50% of ETc in any crop stage studied).

CWP was reduced due to the application of RDI in the flowering and pod-filling stages because the biomass invested in reproductive structures was diminished as water stress promotes abortion or low grain yield. At the same time, in the case of RDI during vegetative growth, applying 50% of ETc also impacted CWP (Table 8). Other studies show that applications of 50% of full irrigation in the flowering stage in comparison to the pod filling stage generate significant reductions in CWP, the prior being more sensitive than the latter; so, in our study (Chapter 2), flowering is confirmed as the most sensitive stage in which the application of RDI impacts CWP more profoundly (Hirich et al., 2014).

5.2. UAV-derived thermal and multispectral imagery predicts grain yield and crop water productivity in chickpea (*Cicer arietinum* L.)

Several studies have demonstrated the usefulness of the canopy temperature depression index (CTD) and the Normalized Difference Vegetation Index (NDVI) in determining crop yield and water productivity (Nemeskéri et al., 2017; Hou et al., 2019: Neupane, 2020; De Santis et al., 2022). However, few efforts have been undertaken to evaluate water-saving strategies, such as partial root-zone drying irrigation (PDI), regulated deficit irrigation (RDI), and sustained deficit irrigation (SDI) using remote information. In this sense, our results indicated that both the CTD and the NDVI (Figure 10) detected the variations imposed by the different irrigation treatments (over-irrigation, full irrigation, and deficit irrigation like PDI, RDI, and SDI) in the two plants' spatial arrangement (bed-system and single-row).

The CTD had better predictive capabilities than NDVI. The highest irrigation treatments had lower CTD values (Figure 10C); likewise, the single-row system treatments led to lower CTD values than those that used the bed system. Additionally, grain yield (GY, Figure 10A) and crop water productivity (CWP, Figure 10B) presented lower values in treatments with higher CTD. This behavior is consistent with the results found by Kumar et al. (2017) and Hou et al. (2019), who found that the increase in CTD was associated with the reduction of grain yield in crops such as soybeans (*Glycine max* L.), where for each degree Celsius the yield was reduced from 273 to 304 kg ha^{-1} of grain. In our work, each increase in one Celsius degree in CTD generated a loss of 220 kg ha^{-1} in GY (Figure 12C) and a reduction of 0.078 kg m^{-3} in CWP (Figure 12D).

Deficit irrigation treatments also led to lower NDVI values (Figure 10D); this trend was more remarkable in those established under bed system plant arrangements, which also had lower values of GY (Figure 10A) and CWP (Figure 10B). When plants grow under a water deficit, their leaves reflect less near-infrared and red irradiation, which causes lower NDVI values (Marín et al., 2020; Solgi et al., 2023). This behavior is consistent across various crops (Grados et al., 2020; Tavares et al., 2022).

CTD and NDVI decreased from using bed-systems concerning single-row systems; this might be due to the distance from the plant to the drip tape (plant 0.2 m from both sides of the drip), making it difficult to access the roots to irrigation water, as has been found in other crops under drip irrigation conditions (Firouzabadi et al., 2021; Samoy-Pascual et al., 2022). However, the plant's proximity to the drip tape increases the material cost per surface unit (Firouzabadi et al., 2021; Samoy-Pascual et al., 2022).

In our dataset, the deficit irrigation strategies using the PDI resulted in larger GY and higher CWP, which agrees with previous reports (Iqbal et al., 2020), indicating that this technique is more efficient in the use of water without diminishing crop yields.

5.3. Integrated analysis of experiments (deficit irrigations implementation)

The positive response of chickpeas in grain yield, dry plant weight, grains per plant, and pod per plant to increases in the volumes of irrigation is consistent with previous trends reported by Kumar et al. (2021) and Mhaske (2019). This consequent increase in yield has been attributed to a level of total irrigation that maximized carbon uptake, contributing to a better establishment, growth, and development, which results in an increase in the transfer of assimilated products to the reproductive organs, in addition to reducing flowers and pods abortion (Singh et al., 2016).

The regression models of grain yield, plant dry weight, pod, and grain per plant have been curvilinear (Figure 14). In this sense, Ray et al. (2023) pointed out that the legume production function shows a linear relationship with the level of irrigation, while they argued that the function can take a curvilinear form with the drop in yield linked to an excess of water that generates effects to the plant due to a waterlogging condition, lack of aeration in the root zone, nutrient washing or the presence of diseases. In this study, curvilinear responses can be attributed to implicit aspects inside the value of total irrigation (independent variable) considered for the regression analysis, *i.e.*, the effects of deficit irrigation treatments, plant arrangements (bed-system *vs* single-row system), and year effects.

Concerning the variables, plant height, pod, and grains per plant are favored by the level of irrigation, while grain caliber is reduced. In this topic, Korbu et al. (2022), when evaluating the response of chickpeas to different moisture levels: no stress, mild stress and severe stress under furrow irrigation in Ethiopia, found a decrease in plant height (0.48 to 0.38 m), 100 seed weights (31 to 27 g) and grain yield (2218 to 1650 kg ha^{-1}) linked to water diminishment; water restriction affected in a greater degree the number of pods (-29%) and the consequent number of grains, while the one hundred grain weight lost 13 % with respect no stress condition. In our study, considering the slope in the regression models (Figure 14), pod and grain per plant were more affected by plant height and grain caliber.

The negative relationship found in crop water productivity agrees with reports by Singh et al. (2016), who mentioned that this variable should not be taken as an isolated indicator of the selection of outstanding irrigation treatments; this is caused by treatments with low irrigation or without complementary irrigation have exhibited higher crop water productivity; it has also been argued by Singh et al. (2016) that a linear increase in grain yield does not necessarily mean a higher CWP.

The harvest index response is concordant with previous research reporting that the water deficit applied in reproductive stages increases the allocation of plant resources in the reproductive organs, improving the productivity parameters in the crop (Kang et al., 2008). Kumar et al. (2021) noted that the harvest index increased with irrigation restrictions generated.

Principal components and cluster analysis generate irrigation treatment groups and their description. Group 1 included the irrigation treatments established in the single-row system, *i.e.*, full irrigation (FI-S) and partial root-zone drying irrigation applied during vegetative growth (PDI_{VG}-S), flowering (PDI_F-S) and pod-filling (PDI_{PF}-S). This group presented the highest values of grain yield, plant dry weight, grain, and pod per plant. It is essential to highlight that although this group did not present the highest value of water productivity, as Singh et al. (2016) pointed out, this variable should not be a unique indicator of the selection of outstanding irrigation treatments.

As indicated in the results section, given that the four treatments were considered the same in their productive characteristics, the treatment (PDI_F-S) is considered outstanding, which is the one that used the lowest volume of water among this group and a slight value of water productivity. Thus, Zwart and Bastiaanssen (2004) pointed out that deficit irrigation can increase crop water productivity.

Chapter 6. General conclusions

In accordance with our hypothesis, the use of deficit irrigation allowed to maximize grain yield and improve crop water productivity, with the following particularities:

Regulated deficit irrigation (*i.e*., crop irrigation in specific stages of plant development under the full requirement for optimal plant growth, applied at 75% crop evapotranspiration) in the vegetative stages is the best way to improve CWP when we utilize the bed-system plant arrangement. Applying regulated deficit irrigation in the flowering and pod-filling stages negatively impacts crop water productivity; it is affected even more if the reduction of irrigation reaches 50% of the crop evapotranspiration.

When comparing regulated deficit irrigation, sustained deficit irrigation (*i.e.*, applications of below-optimal water volumes during each irrigation event for the complete crop cycle), and partial root-zone drying irrigation (*i.e.*, irrigation of one side of the plant's roots, but simultaneously exposing to drought the other side of the radicular system) during the flowering stage (75% crop evapotranspiration), favored grain yield and crop water productivity.

Increasing the amount of water applied for chickpeas positively influenced the grain yield and plant phenotypic characteristics, such as dry weight, pod, and grain per plant, while height and grain caliber were less affected. Harvest index and crop water productivity showed a negative relationship with the increase in total irrigation.

When testing very low irrigation treatments, these show higher crop water productivity; in this sense, the crop water productivity variable should not be taken as an isolated indicator of the selection of outstanding irrigation treatments.

According to our hypothesis, using UAV-mounted remote sensing could detect the crop's response to variant irrigation schemes, as well as predict grain yield and crop water productivity with the next particularities:

Both UAV remotely sensed Canopy Temperature Depression (CTD) and Normalized Difference Vegetation Index (NDVI) can be used as a key tool to predict grain yield and crop water productivity in chickpeas. NDVI had no statistical significance to discriminate across treatments, however, it can still predict crop water productivity and gran yield, although in a less precise way in comparison to CTD. The end of the flowering stage was the best time in phenology to predict grain yield and crop water productivity.

We consider it necessary to assess other levels of Kc in the stages of cultivation, which will allow an exploration of productive potential, refining the levels of ETc, seeking to increase grain yield and CWP, which would allow for the optimization of the implementation of deficit irrigation schemes worldwide.

We recommend expanding the evaluation of these indices in different crops, employing additional plant response variables, such as plant growth, health status, and water stress, to optimize crop productivity and its application in precision agriculture schemes.

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Supplementary materials

Supplementary 1

Table 18. Analysis of variance of eight productivity, yield, quality, and growth variables of chickpeas across deficit irrigation treatments during two consecutive years of experiments (2020 and 2021) in Todos Santos, Baja California Sur, Mexico.

Year	**Grain yield and quality***		**Plant growth***				**Productivity***	
	GY	**Cal**	**H**	**PDW**	**PP**	**GP**	**HI**	**CWP**
2020	861.8 ± 260.7a	49.4 ± 4.4a	0.44 ± 0.03a	11.4 ± 2.8b	7.7 ± 2.0a	8.9 ± 2.6a	0.47 ± 0.06a	0.90 ± 0.2a
2021	944.7 ± 230.1a	46.1 ± 3.0b	0.37 ± 0.02b	14.9 ± 2.3a	8.2 ± 1.4a	9.3 ± 1.7a	0.41 ± 0.03b	0.66 ± 0.1b

GY= grain yield, Cal= grain caliber, H= plant height, PDW = plant dry weight, PP = pods per plant, GP= grain per plant, HI= harvest index, CWP= crop water productivity. Y= year, B= block, T= treatments. DF=Degrees of freedom. CV= coefficient of variation. ^{ns}= non-significant ($p \geq 0.05$), Bold with * = $p < 0.05$, ** = $p < 0.01$. Values in each column inside every variable represent mean squared error.

Table 19. Differences in grain yield and quality, plant growth and crop water productivity of chickpeas between two consecutive years of deficit irrigation experiments (2020, 2021) in Todos Santos, Baja California Sur, Mexico.

Source of variation	**DF**	**Grain yield and quality**		**Plant growth**				**Productivity**	
		GY	Cal	H	PDW	PP	GP	HI	CWP
Y	1	109951.92^{ns}	***182.31*****	***0.0961*****	***195.79*****	3.95^{ns}	2.72^{ns}	***0.0663*****	***0.89*****
B (Y)	6	85214.48^{ns}	11.19^{ns}	0.0005^{ns}	17.68**	6.53**	10.40**	0.0035^{ns}	0.07*
T	7	***202004.16*****	***37.30*****	***0.0028*****	***17.65*****	***9.27*****	***15.74*****	***0.0086*****	***0.10*****
Y*T	7	29914.49^{ns}	12.06^{ns}	***0.0016*****	3.96^{ns}	2.49^{ns}	4.48^{ns}	0.0033^{ns}	0.03^{ns}
Error	42	38453.76	11.45	0.0004	3.80	1.53	2.75	0.0019	0.03
Media		903.33	47.79	0.40	13.18	7.96	9.18	0.44	0.78
CV (%)		21.70	7.08	5.21	14.79	15.53	18.07	9.84	22.44

GY= grain yield, Cal= grain caliber, H= plant height, PDW= plant dry weight, PP= pods per plant, GP= grain per plant, HI= harvest index, CWP= crop water productivity. Y= year, B= block, T= treatments. *Mean ± SD. ^{ab} Different letter between years, in the same column, indicates statistically significant ($p \leq 0.05$, LSD).

Supplementary 2

Table 20. Date and water volume applied to each treatment to test the association between thermal and multispectral indices with grain yield and productivity in chickpea at Todos Santos, Baja California Sur, Mexico.

Rain (R) or irrigation (I) event	Date Year 2022	Crop stage (range of das or GDD)	Water volume applied in m^3 ha^{-1}							
			OI-B	FI-B	RDI$_{VG}$-B	SDI-B	FI-S	PDI$_{VG}$-S	PDI$_{F}$-S	PDI$_{PF}$-S
R-1	Dec 31	Germination*	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00
I -1	Jan 5	0 -15 das	124.70	124.70	124.70	124.70	124.70	124.70	124.70	124.70
I -2	Jan 8	0–272.4 GDD	83.25	83.25	83.25	83.25	83.25	83.25	83.25	83.25
		Subtotal irrigation	***407.9***	***407.9***	***407.9***	***407.9***	***407.9***	***407.9***	***407.9***	***407.9***
I -3	Jan 16	Vegetative growth 16 – 43 das 272.4-695 GDD	63.83	51.06	38.30	38.30	51.06	38.30	51.06	51.06
I -4	Jan 21		123.31	98.65	73.99	73.99	98.65	73.99	98.65	98.65
I -5	Jan 26		125.84	100.67	75.50	75.50	100.67	75.50	100.67	100.67
I -6	Jan 30		105.60	84.48	63.36	63.36	84.48	63.36	84.48	84.48
I -7	Feb 03		108.76	87.01	65.26	65.26	87.01	65.26	87.01	87.01
I -8	Feb 09		98.01	78.41	58.81	58.81	78.41	58.81	78.41	78.41
		Subtotal irrigation	***625.3***	***500.2***	***375.2***	***375.2***	***500.2***	***375.2***	***500.2***	***500.2***
I -9	Feb 13	Flowering 44 – 70 das 695-1121.1GDD	263.82	211.06	211.06	158.29	211.06	211.06	158.29	211.06
I -10	Feb 17		331.47	265.18	265.18	198.88	265.18	265.18	198.88	265.18
I -11	Feb 23		432.94	346.35	346.35	259.76	346.35	346.35	259.76	346.35
I -12	Feb 26		226.62	181.29	181.29	135.97	181.29	181.29	135.97	181.29
I -13	March 02		368.68	294.94	294.94	221.21	294.94	294.94	221.21	294.94
I -14	March 06		361.91	289.53	289.53	217.15	289.53	289.53	217.15	289.53
		Subtotal irrigation	***1985.4***	***1588.3***	***1588.3***	***1191.2***	***1588.3***	***1588.3***	***1191.2***	***1588.3***
I -15	March 12	Pod-filling 71 – 103 das 1121.1-1600 GDD	167.65	134.12	134.12	100.59	134.12	134.12	134.12	100.59
I -16	March 16		124.12	99.29	99.29	74.47	99.29	99.29	99.29	74.47
I -17	March 20		125.29	100.24	100.24	75.18	100.24	100.24	100.24	75.18
		Subtotal irrigation	***417.0***	***333.6***	***333.6***	***250.2***	***333.6***	***333.6***	***333.6***	***250.2***
Total irrigation (T_i), m^3 ha^{-1}			**3435.8**	**2830.2**	**2705.1**	**2224.6**	**2830.2**	**2705.1**	**2433.1**	**2746.8**
% of water applied with respect to full irrigation treatments			*121.3*	*100.0*	*95.5*	*78.60*	*100.0*	*95.5*	*85.9*	*97.0*

*Germination considered an accumulated water volume of 407.95 m^3 ha^{-1}. Dark, middle, and light blue colors indicate 125, 100 and 75 % of ETc applied in the specific growth stage. **OI-B**= Over irrigation applied during VG, F, and PF stages + bed system with a double row of plants. **FI-B**= Full irrigation applied during VG, F, and PF stages + bed system with a double row of plants. **RDI$_{VG}$-B**= Regulated deficit irrigation applied in VG stage + bed system with double row of plants. **SDI-B**= Sustained deficit irrigation + bed system with a double row of plants. **FI-S**= Full irrigation applied during VG, F and PF stages + plants in single row. **PDI$_{VG}$-S**= Partial root-zone drying irrigation applied during VG stage + plants in single row. **PDI$_{F}$-S**= Partial root-zone drying irrigation applied during F stage + plants in a single row. **PDI$_{PF}$-S**= Partial root-zone drying irrigation applied during PF stage + plants in single row. GDD= Growing degree days.

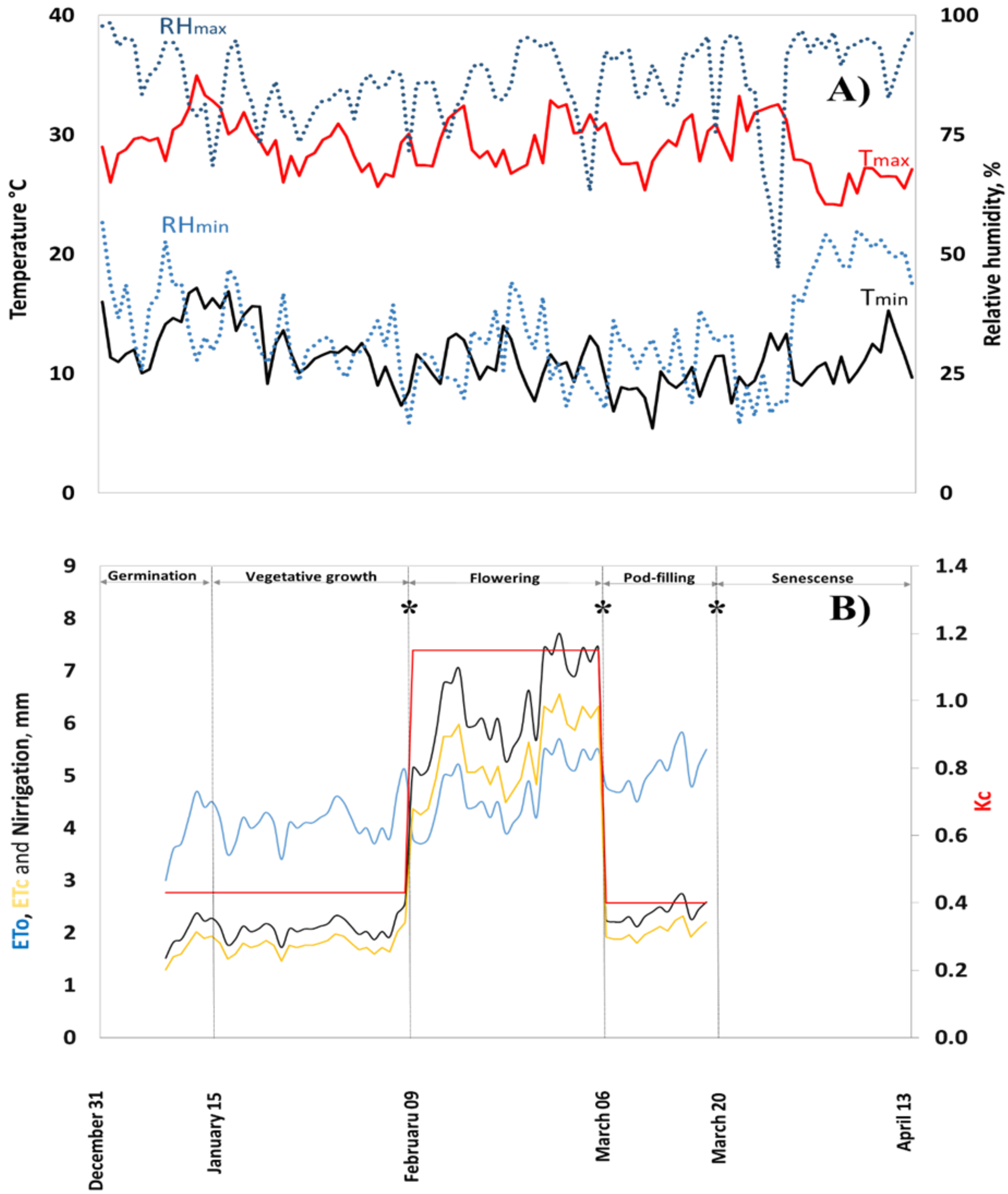

Figure 17. A) Temperature and relative humidity from December 31, 2021 – April 13, 2022 at the Todos Santos Experimental Station (INIFAP, Mexico). T_{max} and T_{min} represent daily maximum and minimum temperature in °C. RH_{max}, and RH_{min} represent daily maximum and minimum relative humidity in percentage. B) Potential evapotranspiration (ETo, blue), crop evapotranspiration (ETc, yellow), crop coefficient (Kc, red) and net irrigation requirement ($N_{irrigation,}$ black) for the experimental chickpea variety. *Asterisks indicate the date of UAV flights.

Table 21. Canopy temperature depression (CTD) calculation from canopy temperature (CT) and air temperature (AT) of each irrigation treatment at three chickpea growth stages.

Irrigation treatment	Block	Vegetative growth (VG)			Flowering (F)			Pod-filling (PF)			*Average CTD, °C
		CT, °C	AT, °C	CTD, °C	CT, °C	AT, °C	CTD, °C	CT, °C	AT, °C	CTD, °C	
OI-B	I	30.65	26.18	4.47	29.85	26.32	3.53	40.40	29.22	11.18	6.39
	II	32.10	26.18	5.92	30.20	26.32	3.88	39.75	29.22	10.53	6.78
	III	32.40	26.18	6.22	33.85	26.32	7.53	43.00	29.22	13.78	9.18
	IV	33.75	26.18	7.57	32.20	26.32	5.88	42.55	29.22	13.33	8.93
FI-B	I	35.15	26.18	8.97	31.95	26.32	5.63	43.00	29.22	13.78	9.46
	II	31.85	26.18	5.67	31.10	26.32	4.78	41.20	29.22	11.98	7.48
	III	33.60	26.18	7.42	32.60	26.32	6.28	41.80	29.22	12.58	8.76
	IV	36.50	26.18	10.32	32.85	26.32	6.53	43.95	29.22	14.73	10.53
RDI_{VG}-B	I	33.55	26.18	7.37	33.50	26.32	7.18	42.80	29.22	13.58	9.38
	II	36.30	26.18	10.12	32.35	26.32	6.03	44.50	29.22	15.28	10.48
	III	33.25	26.18	7.07	31.60	26.32	5.28	41.80	29.22	12.58	8.31
	IV	37.70	26.18	11.52	34.20	26.32	7.88	44.10	29.22	14.88	11.43
SDI-B	I	35.55	26.18	9.37	31.70	26.32	5.38	42.30	29.22	13.08	9.28
	II	33.80	26.18	7.62	32.05	26.32	5.73	44.00	29.22	14.78	9.38
	III	33.85	26.18	7.67	30.60	26.32	4.28	41.15	29.22	11.93	7.96
	IV	35.20	26.18	9.02	33.00	26.32	6.68	44.50	29.22	15.28	10.33
FI-S	I	33.30	26.18	7.12	29.20	26.32	2.88	39.90	29.22	10.68	6.89
	II	32.45	26.18	6.27	29.70	26.32	3.38	42.20	29.22	12.98	7.54
	III	30.85	26.18	4.67	27.65	26.32	1.33	41.60	29.22	12.38	6.13
	IV	31.60	26.18	5.42	29.60	26.32	3.28	40.35	29.22	11.13	6.61
PDI_{VG}-S	I	33.95	26.18	7.77	33.95	26.32	7.63	42.70	29.22	13.48	9.63
	II	32.95	26.18	6.77	29.15	26.32	2.83	40.00	29.22	10.78	6.79
	III	30.35	26.18	4.17	27.20	26.32	0.88	39.90	29.22	10.68	5.24
	IV	33.20	26.18	7.02	28.50	26.32	2.18	39.55	29.22	10.33	6.51
PDI_{F}-S	I	31.70	26.18	5.52	30.05	26.32	3.73	41.70	29.22	12.48	7.24
	II	31.25	26.18	5.07	30.25	26.32	3.93	42.10	29.22	12.88	7.29
	III	30.85	26.18	4.67	28.10	26.32	1.78	40.35	29.22	11.13	5.86
	IV	32.40	26.18	6.22	29.25	26.32	2.93	39.80	29.22	10.58	6.58
PDI_{PF}-S	I	33.75	26.18	7.57	28.75	26.32	2.43	40.55	29.22	11.33	7.11
	II	31.15	26.18	4.97	26.40	26.32	0.08	39.85	29.22	10.63	5.23
	III	30.95	26.18	4.77	29.40	26.32	3.08	40.15	29.22	10.93	6.26
	IV	34	26.18	7.82	30.15	26.32	3.83	41.00	29.22	11.78	7.81

*Average obtained from CTD of each treatment repetition at three growth stages. AT= Air temperature at the moment of image acquisition. **OI-B**= Over irrigation applied during VG, F, and PF stages + bed system with a double row of plants. **FI-B**= Full irrigation applied during VG, F, and PF stages + bed system with a double row of plants. **RDI_{VG}-B**= Regulated deficit irrigation applied in VG stage + bed system with double row of plants. **SDI-B**= Sustained deficit irrigation + bed system with a double row of plants. **FI-S**= Full irrigation applied during VG, F and PF stages + plants in single row. **PDI_{VG}-S**= Partial root-zone drying irrigation applied during VG stage + plants in single row. **PDI_{F}-S**= Partial root-zone drying irrigation applied during F stage + plants in a single row. **PDI_{PF}-S**= Partial root-zone drying irrigation applied during PF stage + plants in single row.

Table 22. Normalized difference vegetation index (NDVI) values of chickpea plant on each irrigation treatment at three growth stages.

Irrigation treatment	Block	Vegetative growth	Flowering	Pod-filling	*Average NDVI
OI-B	I	0.386	0.510	0.104	0.334
	II	0.346	0.520	0.133	0.333
	III	0.352	0.436	0.048	0.279
	IV	0.332	0.449	0.111	0.298
FI-B	I	0.340	0.440	0.056	0.279
	II	0.389	0.466	0.103	0.319
	III	0.360	0.452	0.063	0.292
	IV	0.324	0.461	0.087	0.291
RDI_{VG}-B	I	0.266	0.424	0.055	0.248
	II	0.330	0.444	0.066	0.280
	III	0.362	0.446	0.069	0.292
	IV	0.321	0.440	0.065	0.275
SDI-B	I	0.353	0.458	0.063	0.291
	II	0.352	0.466	0.068	0.295
	III	0.344	0.463	0.116	0.308
	IV	0.349	0.441	0.059	0.283
FI-S	I	0.370	0.493	0.077	0.313
	II	0.312	0.467	0.062	0.280
	III	0.394	0.513	0.107	0.338
	IV	0.386	0.515	0.093	0.331
PDI_{VG}-S	I	0.249	0.409	0.046	0.235
	II	0.332	0.502	0.112	0.315
	III	0.364	0.535	0.098	0.333
	IV	0.320	0.515	0.121	0.318
PDI_{F}-S	I	0.355	0.472	0.081	0.303
	II	0.323	0.461	0.082	0.289
	III	0.404	0.511	0.084	0.333
	IV	0.335	0.485	0.084	0.301
PDI_{PF}-S	I	0.398	0.525	0.081	0.335
	II	0.392	0.566	0.089	0.349
	III	0.380	0.522	0.057	0.320
	IV	0.329	0.493	0.061	0.294

*Average obtained from NDVI of each treatment repetition at three growth stages. AT= Air temperature at the moment of image acquisition. **OI-B**= Over irrigation applied during VG, F, and PF stages + bed system with a double row of plants. **FI-B**= Full irrigation applied during VG, F, and PF stages + bed system with a double row of plants. **RDI_{VG}-B**= Regulated deficit irrigation applied in VG stage + bed system with double row of plants. **SDI-B**= Sustained deficit irrigation + bed system with a double row of plants. **FI-S**= Full irrigation applied during VG, F and PF stages + plants in single row. **PDI_{VG}-S**= Partial root-zone drying irrigation applied during VG stage + plants in single row. **PDI_{F}-S**= Partial root-zone drying irrigation applied during F stage + plants in a single row. **PDI_{PF}-S**= Partial root-zone drying irrigation applied during PF stage + plants in single row.

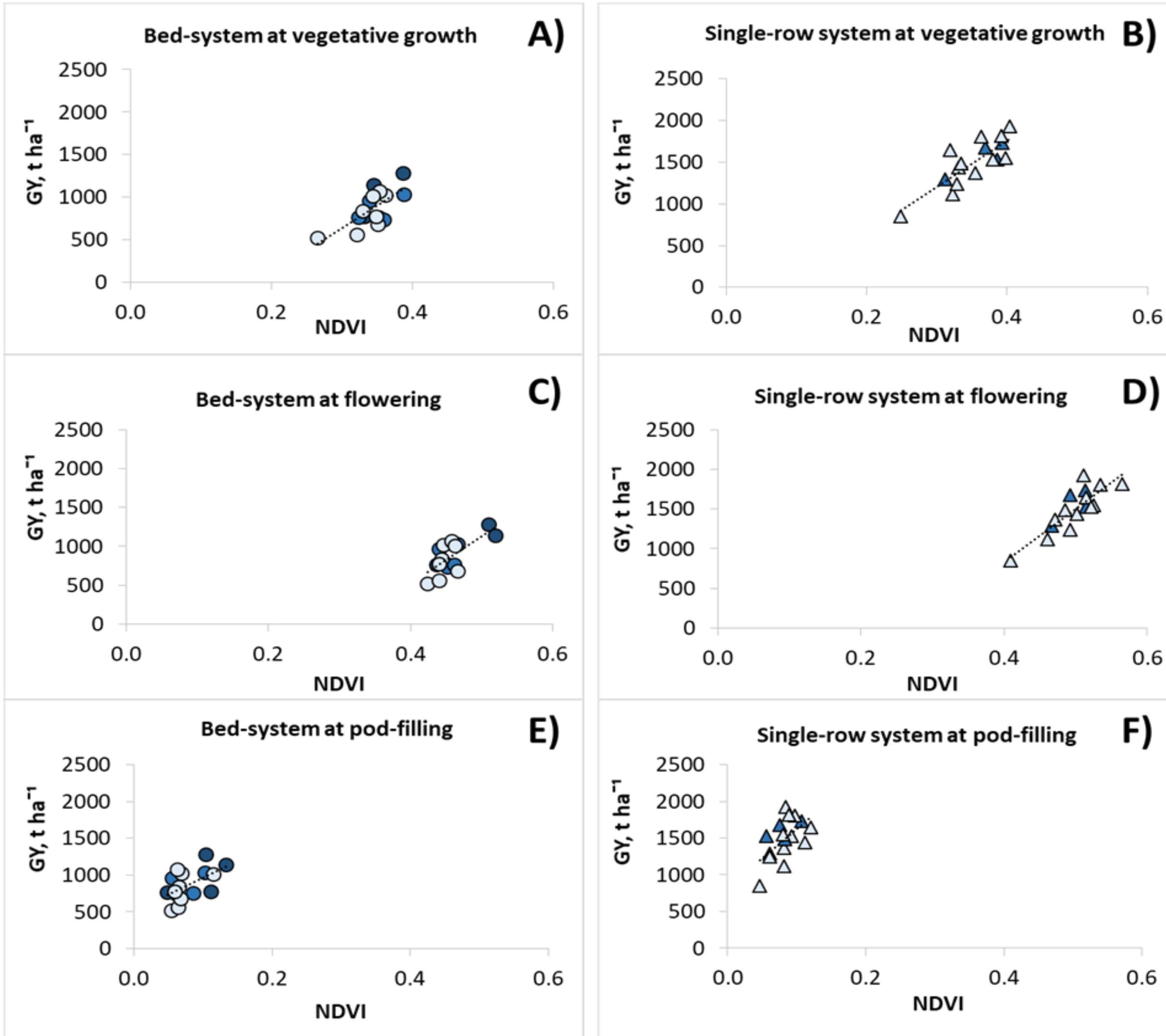

Figure 18. Relationship between GY and NDVI for chickpea at different growth stage and stablished under bed system [A) GY= -938.3 + 5246.3 NDVI, R^2=0.48; C) GY= -1887.1 + 6023.8 NDVI, R^2= 0.52; E) GY= 507.02 + 4553.4 NDVI, R^2= 0.31] and single-row of plant system [B) GY= -473.9 + 5582.8 NDVI, R^2= 0.68; D) GY= -1828.5 + 6660 NDVI, R^2=0.72; and F) GY= 838.18 + 7872 NDVI, R^2= 0.32]. All the regression models presented statistical significance $p \leq 0.02$.

Table 23. Analysis of variance of grain yield (GY), crop water productivity (CWP), canopy temperature depression (CTD) and normalized difference vegetation index (NDVI) of chickpeas across different irrigation treatments during 2022 experiments at Todos Santos Experimental Station, Baja California Sur, Mexico.

Source of variation	DF	GY	CWP	CTD	NDVI
Treatments	7	475613.6**	0.075**	6.92**	0.0009
Blocks	3	69586.6	0.010	2.93	0.0006
Error	21	70873.1	0.009	1.28	0.0006
Total	31	-	-	-	-
Mean	-	1181.44	0.43	7.90	0.30
CV	-	22.53	22.57	14.35	8.27

**p < 0.01. DF=Degrees of freedom. CV= coefficient of variation. ** = $p < 0.01$. Values in each column inside every response variable represent mean squared error

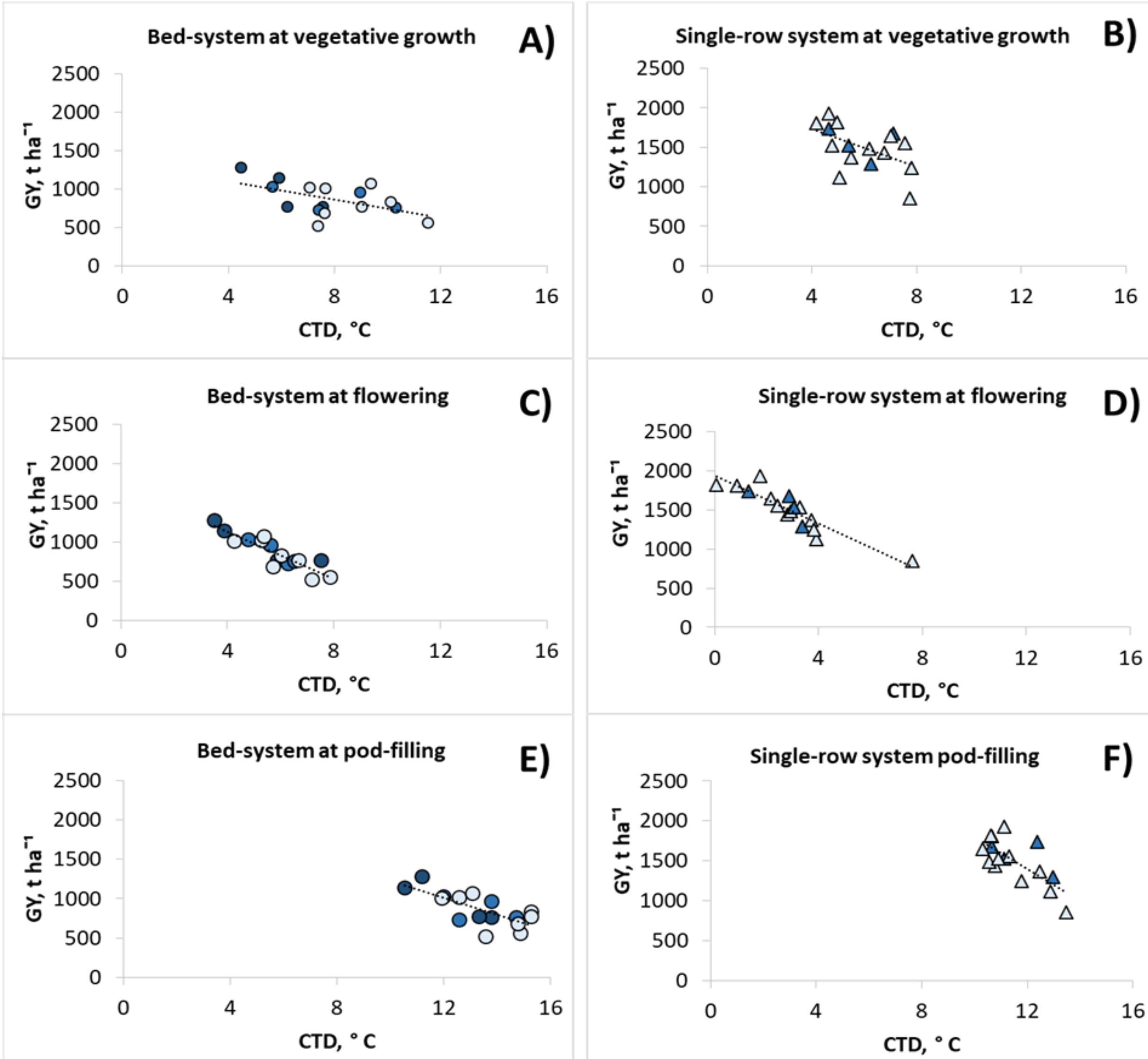

Figure 19. Relationship between GY and CTD for chickpea at different growth stage and stablished under bed system [A) GY= 1334.8 - 59.20 CTD, R^2= 0.27; C) GY= 1745.9 - 152 CTD, R^2= 0.79; E) GY= 2281.8 - 106.11 CTD, R^2= 0.52] and single-row of plant system [B) GY= 2205.2 - 118.5 CTD, R^2= 0.27; D) GY= 1935.8 - 152.56 CTD, R^2= 0.81; F) GY= 3823.9 – 202.27 CTD, R^2= 0.52]. All the regression models presented statistical significance $p \leq 0.03$.