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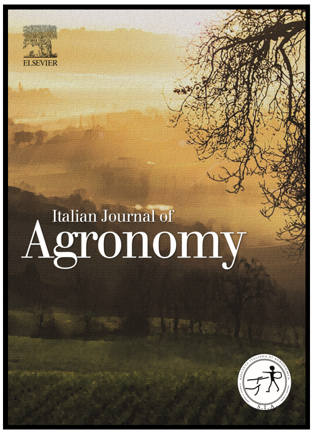
Original Citation:

Impact of Supplemental Irrigation on Yield, Water Productivity, and Economic Profitability of Broad Bean (Vicia faba L., var. minor) / Leonardo Verdi; Anna Dalla Marta. - In: ITALIAN JOURNAL OF AGRONOMY. - ISSN 2039-6805. - ELETTRONICO. - (2025), pp. 0-0.



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PII: S1125-4718(25)00003-9
DOI: https://doi.org/10.1016/j.ijagro.2025.100029
Reference: IJAGRO100029

To appear in: *Italian Journal of Agronomy*

Received date: 19 November 2024
Revised date: 24 January 2025
Accepted date: 26 January 2025

Please cite this article as: Andrea Martelli, Leonardo Verdi, Davide Rapinesi, Itzel Inti Maria Donati, Antonella Di Fonzo, Myriam Ruberto, Anna Dalla Marta and Filiberto Altobelli, Impact of Supplemental Irrigation on Yield, Water Productivity, and Economic Profitability of Broad Bean (Vicia faba L., var. minor), *Italian Journal of Agronomy,* (2025) doi:https://doi.org/10.1016/j.ijagro.2025.100029

Impact of Supplemental Irrigation on Yield, Water Productivity, and Economic Profitability of Broad Bean (Vicia faba L., var. minor)

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Highlights:

- Supplemental irrigation helps reduce variability in broad bean yields and mitigates the impact of fluctuating climatic conditions.
- The average yield of broad beans with supplemental irrigation increased by 40 % compared to rainfed conditions.
- This study helps enhance the sustainability and competitiveness of broad bean cultivation.

Keywords:

Legumes; Economic Water Productivity; Internet of Things; Evapotranspiration; Machine Learning; Sustainability

Abstract

This paper investigates the effects of irrigation and plant density on the yield and water productivity of broad bean in central Italy over two growing seasons (2020-2021 and 2021-2022). The study emphasizes the role of legumes in promoting sustainable and competitive farming systems, with broad bean (Vicia faba L., var. minor) being a promising crop due to its low production costs and resource requirements, particularly water. Optimizing water use and increasing yield are crucial to enhancing the economic viability of broad bean cultivation. We present crop water assessments and evaluate two supplemental irrigation (SI) strategies, a machine learning - based decision support system (ML-DSS) and the crop evapotranspiration estimation approach (ETC), under three plant densities of 40, 50 and 60 plants m^{-1}.

A simplified economic analysis based on water efficiency indicators was implemented to assess the economic profitability of SI on broad bean.

Irrigation significantly increased growth and yield by 40 % on average, compared to rainfed conditions (4.54 Mg ha^{-1} vs. 2.71 Mg ha^{-1}). No significant differences were found in yield (4.42 Mg ha^{-1} *vs* 4.66 Mg ha^{-1}) and water productivity between the ETC and the ML-DSS system (7.57 *vs* 8.00 kg ha^{-1} mm^{-1} on average), although both irrigated treatments significantly outperformed rainfed conditions (5.27 kg ha^{-1} mm^{-1} on average). Under irrigation, higher plant density improved total yield and total yield water productivity (TYWP), particularly in the second year, marked by severe drought (from 3.21 to 4.70 Mg ha^{-1}, increasing from 40 to 60 plants m^{-2}). Results showed that a plant density of 60 plants m^{-2} maximized outputs under irrigated conditions, while a plant density of 50 plants m^{-2} was optimal for rainfed conditions. Supplemental irrigation led to higher and more consistent yields over time. The analysis of economic profitability showed a variation between the two experimental years, with an average gross margin (GM) increase of 42 % and 27 % for irrigated treatments compared to

rainfed ones. However, the high incidence of irrigation water cost (IWC) in the second year significantly reduced economic water productivity, making the irrigated treatments with low plant density economically unsustainable.

Introduction

Broad bean (*Vicia faba* var. minor) is a winter legume cultivated in the Mediterranean region primarily for animal feed and as a green manure. Like other legumes, broad bean fits well into crop rotation following cereals, helping to reduce the use of inorganic nitrogen (N) fertilizers for subsequent crops through biological nitrogen fixation by *Rhizobium* bacteria. Key benefits of incorporating broad bean into crop rotations include: (1) decreased inorganic N fertilizer usage (Aschi et al., 2017), (2) lower greenhouse gas emissions, and (3) improved soil physical properties, such as bulk density, porosity, and water retention at field capacity, which support natural soil fertility. These benefits enhance yield and quality in the subsequent crops (Karkanis et al., 2018; Meng et al., 2021). Thus, broad bean offers significant potential for fostering more sustainable and competitive agricultural systems, and its cultivation is promoted under EU eco-schemes (Karkanis et al., 2018). Several authors propose broad bean as an alternative protein source for livestock feed to replace soybean, which requires high inputs, especially in terms of water (Gatta et al., 2018; Meng et al., 2021). However, broad bean is considered a drought-sensitive crop, with its primary cultivation constraint being high yield variability from year to year due to drought occurring during sensitive phenological stages, such as flowering, pod development, and grain filling (Mwanamwenge et al., 1999; Katerji et al., 2011). Heat stress and fluctuations in precipitation intensity and frequency during the reproductive phase are generally seen as the main factors causing yield variability in broad bean and other crops (Kumari et al., 2017). This susceptibility is due to its relatively shallow root system and limited ability to adjust osmotically to water stress (Ouji et al., 2017). Furthermore, drought negatively impacts symbiotic nitrogen fixation (Bashir et al., 2021; Chammakhi et al., 2022), reducing the potential of broad bean to enhance soil fertility. For these reasons, numerous studies highlight the benefits of irrigation on the growth and yield of broad bean and other legumes in the Mediterranean region, particularly in the context of climate change (Attia, 2013; Di Paolo et al., 2015; Marrou et al., 2021). Broad beans are not typically irrigated in Italian agronomic practices. Yet, the increase in extreme weather events calls for strategies to enhance agricultural resilience, such as supplemental irrigation (SI). Supplemental irrigation can be defined as the addition of small amounts of water to primarily rainfed crops during periods when precipitation is insufficient to meet the moisture needs for normal plant growth (Oweis et al., 1999; FAO, 2002; Nangia et Oweis, 2017). A study conducted on a historical series of agroclimatic indices for broad bean indicated that rainfed yields varied greatly, depending significantly on drought severity, while irrigation led to a notable increase in yield (49 %) and a greater stability over time (Dudek et al., 2018). Similar studies in semi-arid regions of Tunisia, Syria, Turkey and Australia reported a 52 % increase in the average weight of 1000 broad bean seeds with SI (Ouji et al., 2017), and a general improvement in the yield (Oweis et al., 2005; Yazar et al., 2017; Zeleke and Nendel, 2019). In Italy, research on drought effects on broad bean productivity suggests that applying 40 mm of SI during late flowering, when total seasonal precipitation does not exceed 350 mm, significantly enhances yield (Di Paolo et al., 2009). More recently, the combined effects of irrigation and N supply on yield and legumes quality were studied in the Mediterranean region, showing promising results (Di Paolo et al., 2015). In this context, our study investigates a machine learning (ML) approach to scheduling SI. The rise of Internet of Things (IoT) in agriculture, driven by advanced technologies such as ML, is revolutionizing precision irrigation and offers valuable support to farmers (Santini et al., 2023; Donati et al., 2023).

The scientific literature highlights the economic benefits of SI, emphasizing its role in ensuring yield and quality stability for profitable crop production during dry years. Numerous studies suggest that a greater understanding of the economic advantages of irrigation would support decision making in water resource planning (Santini et al., 2023), helping to reduce the vulnerability of agriculture to low water availability during droughts (Ray et al., 2016; Torres et al., 2016; Pang et al., 2024). Unlike previous studies, which generally evaluate SI as a drought mitigation measure across various crops (Morris et al., 2014; El Chami et al., 2015), our research provides an economic assessment of supplemental irrigation for broad beans, focusing on its contribution to increased yields.

Assessing alternative irrigation management strategies aimed at promoting sustainable and efficient water use is crucial. For this purpose, indicators that measure water use efficiency (WUE) in both physical and economic terms are essential (Lorite et al., 2012). Irrigation efficiency indices expressed in monetary units offer valuable insights into the economic benefits for farmers, supporting more informed decision-making regarding economic viability (Pereira et al., 2012). Evaluating these aspects is critical, as farm level water management decisions are influenced by the cost and availability of water resources, as well as the options available to improve irrigation efficiency (Wichelns, 2002). This is especially relevant for managing uncertainty arising from meteorological variability, which can impact productivity and profitability (Vico and Porporato, 2011). The inclusion of an economic analysis in the study aims to assess whether SI can mitigate the adverse effects of climate change while supporting economic sustainability goals, with implications for a circular economy.

The objective of this study is to evaluate the effect of SI, managed using a ML-DSS and the crop evapotranspiration estimation approach (ETC), under different plant densities, on the yield, water productivity, and economic profitability of broad bean (Vicia faba L., var. minor) cultivation under Mediterranean conditions.

To our knowledge, there is limited research in scientific literature using a ML-DSS for optimizing SI in crops. Our research represents an initial effort to develop a water management approach that leverages a ML-DSS to optimize SI for broad bean.

2. Methodology

2.1 Experimental site

This experiment was conducted under open field conditions at La Storta (Rome, Italy, 41°57’55.9’’ N, 12°20’23.3’’ E, 59 m a.s.l.) during 2020-21 and 2021-22 growing seasons. The experimental site falls within CSa climatic zone, characterized by warm, dry summers and precipitation concentrated in winter and spring. Meteorological data collected from 2010 to 2020 by the Integrated Agrometeorological Service of the Lazio region (SIARL), indicate a mean annual temperature of 14.9 °C (with mean maximum and minimum temperatures of 21.9 °C and 9.4 C°, respectively) and a mean annual precipitation of 941 mm. Approximately 70 % of annual precipitation occurs between October and March. Soil samples were taken to assess the main physical-chemical properties in the top 0-30 cm of soil, revealing a clay loam texture (USDA classification), high organic matter content (2.6 %) and a favorable C/N ratio (10.1) (Table 1).

Table 1.

2.2 Trial design and agricultural practices

Two irrigation methods were compared alongside three plant densities (40, 50 and 60 plants m^{-2}, hereinafter referred to as D40, D50 and D60), against a non-irrigated control group referred to as rainfed. A split-plot design, with three replications was used: irrigation treatments were assigned to the main plots (9.0 m x 3.0 m in size), plant density to the subplots (3.0 m x 3.0 m in size) on a net area of 243 m^2 plus approximately 30 m^2 buffer zone in total. The broad bean crop followed a grassland; seedbed preparation was carried out according to standard practice, including shredding the residues of previous crop and tilling the soil with a heavy-duty disc harrow to a depth of approximately 18 cm. Broad bean (var. Chiaro di Torrelama) was sown on 12 November, 2020, and 8 November, 2021, with harvest occurring in July. To achieve D40, D50 and D60 plant densities, 24 g m^{-2}, 29 g m^{-2}, and 34 g m^{-2} of seed were sown, respectively, considering a thousand-seed weight of 460 g and a germination rate of 90–95 %.

A pre-sowing fertilization with 100 kg ha^{-1} of triple superphosphate (Siriac®: 46 %) was applied. Due to low weed incidence, the seedbed preparation was sufficient for weed control in both years.

2.3 Irrigation management

Irrigation was performed using sprinkler irrigation, aimed at providing 100 % of the daily crop evapotranspiration (ET_c). In the experimental trial, the sprinklers were positioned considering the height of the field beans, and the throw was correctly adjusted to avoid interference problems between plots. Two irrigation management methods were employed: FAO-56 two-step approach to ET_c estimation and an integrated ML-DSS based approach. For the first method, daily ET_c was calculated by multiplying the reference evapotranspiration (ET_0) by crop coefficients (Kc), which varies according to the phenological phase. These coefficients were based on conditions similar to our experimental site, with values ranging from 0.15 to 0.30 from sowing (BCCH 0-00 to crop establishment (BCCH 1-19), 0.35 during the formation of side shoots (BCCH 2-20) to inflorescence emergence (BCCH 5-59), 1.10 from beginning of flowering (BCCH 6-60) to fruit set (BCCH 7-70) and 0.15 until harvest (BCCH 8-89), which occurred from July 28 to 30. The Hargreaves formula was used to estimate ET_0:

(1) $$\mathrm{ET}_0 = 0.023\ (Tmean + 17.28)\ Ro\ (T\max - T\min)\ 0.5$$

Where: Ro = solar radiation at a given month and latitude (mm day^{-1}); Tmean = daily mean temperature (°C); Tmax = daily maximum temperature (°C); Tmin = daily minimum temperature (°C).

In the ETC treatment the irrigation started once the difference between the calculated crop water requirements (ET_c), and the precipitation accumulation reached the threshold of 40 mm. Regarding the second treatment, the ML-DSS used for irrigation scheduling is a commercial product designed for predictive irrigation optimization. This cutting-edge irrigation management system collects, registers and analyzes data from various sources, including IoT sensors (Irrometer®, WATERMARK Soil Moisture Sensors) located throughout the experimental field and weather forecast services, to develop a machine learning model of the soil water balance. The model predicts soil water potential for a specific terrain and crop, integrating soil water potential, crop evapotranspiration, precipitation, irrigation and meteorological data collected in the field (Umutoni and Samadi, 2024). The irrigation recommendations aim to maintain the soil water potential below field capacity (10 kPa), a threshold consistent with the findings of previous studies. The decision support system integrates ML, automated irrigation control, data storage, and a graphical user interface. The hardware includes the µMETOS NB-IoT weather station and a data logger linked to WATERMARK soil moisture sensors at varying depths to monitor soil water potential. The DSS, developed in Java and Python, employs:

1. Soil water balance prediction via ML
2. Irrigation optimization using a genetic algorithm

The first layer models soil water balance using ML to forecast soil water potential over the next five days, operating with a three-hour time step. The second layer generates irrigation recommendations based on these predictions. Optimization is achieved through a genetic algorithm, a heuristic method inspired by natural selection designed to determine the optimal irrigation schedule, including the timing and water volume (expressed in m^3 ha^{-1}).

The seasonal water consumption of broad beans, known as ET max, was calculated annually for each irrigation treatment using the soil water balance equation (2). These values were used to calculate the crop's water productivity indices.

(2) $ET = P + I - R + Cr \pm \Delta C$

Where ET represents water consumption (mm), P stands for precipitation (mm), and I is the total irrigation water applied (mm). Runoff losses (R) were assumed to be zero, as precipitation never exceeded the soil infiltration rate. Capillary rise (Cr) was considered negligible. ΔC signifies the difference in soil water content between seeding and harvest (mm).

2.4 Meteorological data

Meteorological data were collected using an automatic weather station, specifically the µMetos NV-IoT, a LPWAN weather (Pessl instruments) (Weiz, Austria). This station was installed in the field to record daily mean, maximum, and minimum temperatures (°C), mean, minimum and maximum relative humidity (%), solar radiation (MJ m^{-2}), wind speed (m s^{-1}), precipitation (mm), and daily ET_0 (mm day^{-1}). Continuous monitoring was carried out throughout the two growing seasons.

The meteorological data were used to compute the relative precipitation index (RPI), calculated as the ratio between the mean annual precipitation during the cropping season and the monthly historical annual mean precipitations of the area (Bek et al., 2002). A value greater than 1.00 indicates that precipitation was above the historical mean, while a value less than 1.00 indicates that precipitation was below the historical mean. The values of RPI reported for descriptive purposes, were also expressed as percentage in the text.

2.5 Crop growth and yield

At harvest, broad bean was sampled to measure aboveground dry biomass per plant (DB_{plant}), stem length, and grain yield per plant (Y_{plant}) from three representative plants per plot. Canopy cover (%) was measured during the crop season using Canopeo® software (Patrignani & Ochsner, 2015). Measurements (in three replicates) were taken at four time points during the 2020-21 cropping season: 20 January, 24 February, 10 June, and 2 July, and on four time points during the 2021-22 cropping season: 10 December, 21 January, 21 March, and 2 July. The harvest index (HI) was calculated after determining grain yield and aerial biomass using the following equation:

(3)

$$HI = \frac{Grain\ yield\ (kg\ ha^{-1})}{Total\ aboveground\ dry\ biomass\ (kg\ ha^{-1})}$$

Dry biomass water productivity (DBWP) was calculated as the ratio of total aboveground dry matter at harvest (DW, kg ha^{-1}) to total water used (ET); total yield water productivity (TYWP) was calculated by multiplying the ratio of yield to the total aboveground plant biomass with DBWP, according to the following equation (Molden et al., 2007):

(4) $DBWP\ (kg\ ha^{-1}mm^{-1}) = \frac{Total\ above\ ground\ dry\ biomass\ (kg\ ha^{-1})}{ET\ (mm)}$

(5) $TYWP\ (kg\ ha^{-1}mm^{-1}) = DBWP \cdot \frac{Grain\ yield\ (kg\ ha^{-1})}{Total\ dry\ biomass\ (kg\ ha^{-1})}$

2.6 Economic profitability of agronomic and irrigation strategies

The profitability and economic efficiency of different irrigation systems were assessed by analyzing water use efficiency and productivity. To demonstrate any potential change in profitability as a result of increased water use, we apply a method based on economic water efficiency indicators. In this context, for each irrigation treatment, gross economic water productivity (GEWP) (6) was calculated by dividing the gross margin (GM) of production with the amount of irrigated water used (IWU, m^3) (Fernandez et al., 2020; Perelli et al., 2024; Toffanin et al., 2024).

(6) $EWP\ (€\ m^{-3}) = \frac{Gross\ margin\ (€\ ha^{-1})}{Irrigation\ water\ used\ (m^3\ ha^{-1})}$

The GM was calculated as the difference between the crop economic value (CEV, € ha^{-1}) and the variable costs (VC, € ha^{-1}), which include all costs associated with the irrigation practice (IC), seeds (SC), fertilization (FC) and seasonal labor cost (LC) for soil preparation, sowing, and harvesting (7).

(7)

$$GM\ (€\ ha^{-1}) = CEV\ (€\ ha^{-1}) - IC\ (€\ ha^{-1}) - SC\ (€\ ha^{-1}) - FC\ (€\ ha^{-1}) - LC\ (€\ ha^{-1})$$

The CEV was calculated by multiplying the total yield (TY, Mg ha^{-1}) by the market price (€ t^{-1}) published by the Chamber of Commerce of Bologna for the experimental years (340.00 € t^{-1} and 442.00 € t^{-1} in 2021 and 2022, respectively) (CCB, 2021; 2022). The cost of irrigation water (IC) was estimated at 0.45 € m^{-3}, and includes the cost of fuel required to distribute irrigation water (0.29 € m^{-3}) and the tariff for irrigation services in the study area (0.16 € m^{-3}). The SC and FC refers to costs actually incurred during the two experimental years for the purchase of seeds (850.00 € t^{-1}) and fertilizer (786.00 € t^{-1}) while LC takes into account the tariffs of contractors in Italy (306.00 € ha^{-1}). Additionally, the economic water productivity ratio (EWPR) was specifically calculated for the irrigation treatments to express economic productivity in monetary terms (€). It represents the economic value generated per unit of water used, calculated as a ratio between the CEV and IC (Pereira et al., 2012; Bui, 2017). A high EWPR indicates more efficient use of water, generating greater economic returns for each unit of water used. Finally, the impact of irrigation costs on experimental treatments was assessed by calculating the incidence of irrigation costs (IWC) and the ratio of EWPR. Irrigation costs allow the weight of water costs on variable costs to be quantified, and it is given by the ratio of IC to variable costs according to the following equation (8) (Perelli et al., 2024):

(8)

$$IWC = \frac{IC}{VC} \cdot 100$$

2.7 Statistical analysis

The significance of fixed effects (irrigation, plant density and year) including main effects and interactions, was assessed using analysis of variance (ANOVA). Year was treated as a fixed effect to specifically analyse its impact, given the limited number of years considered. Random effects were included to account for variability in the experimental design, with subplots nested within main plots to reflect the hierarchical structure. Pairwise comparisons of treatment means were performed using Tukey's post-hoc test, with results averaged across levels of plant density and irrigation treatments. All statistical analyses were performed using R software (version 4.3.1), employing the lme4 package for model fitting (Bates et al., 2015) and the emmeans package (Lenth, 2022) for post-hoc analyses, with significance set at $p < 0.05$.

3. Results and discussion

3.1 Meteorological conditions and irrigation volumes

Meteorological data collected from November to July (269 days) for each experimental year revealed high variability, particularly in terms of maximum mean temperatures and precipitation distribution (Figure 1).

Figure 1.

The mean temperature during the crop cycle was 12.4 °C and 13.6 °C, in the first and in the second year, respectively. Similar precipitation amounts (408 and 476 mm), but highly different ET_0 (621 mm and 842 mm) were recorded during the two years of the study from November to July (Table 2).

Table 2.

Comparing meteorological data with the historical series from November to July, in the first year, the mean temperature was slightly below the historical value of 12.5°C, while in the second year, temperatures exceed the historical mean by 1.1°C with a deviation of ±1 SD. In both years, precipitation were below the 80th percentile of the historical mean (650 mm). Precipitation during one of the critical growth periods for the crop (March to May) showed a decrease of 70 % and 80 % in the 2020-21 and 2021-22, respectively, in March, while in April it changed by +34 % and -57 %, and in May by -65 % and -94 %, compared to the historical series (Table 2). The high temperature recorded from April onwards, which caused an increased ET_0, together with a precipitation scarcity, probably led to a limited water availability for the crop, especially in the second year. In the first year, favorable temperature and adequate precipitation resulted in a lower need for irrigation to compensate for evapotranspiration losses. The average total irrigation volume was 50 mm in the first year and 146 mm in the second year. The treatment with irrigation advice (ML-DSS) scheduled more frequent irrigations compared to the ETC method (Table 3).

Table 3.

3.2 Effect of year

ANOVA reveals that the year (Y) had a significant effect on nearly all parameters (Table 4).

Table. 4

In the first year, TDB was on average greater than in the second year (7.03 Mg ha^{-1} and 4.99 Mg ha^{-1}, respectively) (Table 5). Similar results were recorded for Y_{plant} and TY, with significant differences due to the different meteorological conditions that generally favored the first year compared to the second one. The effect of the year on the studied parameters was also observed in similar studies on broad bean (Di Paolo et al., 2015; Fang et al., 2023), which highlight the impact of the meteorological conditions on growth and yield of this crop. During the second year, a severe drought occurred from flowering (April) to grain filling (May-June) where recorded precipitation was 32 mm, significantly lower than the 153 mm recorded in the first year (Table 2). Additionally, higher cumulative ET_0 values were observed (496 mm). In the second year, the irrigated treatments (ETC and ML-DSS) maintained high yields and biomass production, although lower than the first year (Table 5). The rainfed treatment, on the other hand, showed a considerable yield decrease.

Table 5.

On average, across both years, the irrigated treatments determined a yield of 4.54 Mg ha^{-1}, which was 40 % higher than the 2.70 Mg ha^{-1} observed for the rainfed treatment (Table 5). These results align with studies on the response of broad bean under different irrigation conditions, where a significant effect of irrigation was observed during the period of drought susceptibility for the crop (April-May). Di Paolo et al. (2015) reported a positive yield response to irrigation treatments in the most unfavorable climatic period, recording lower production values in rainfed than in irrigated treatment (2.40 Mg ha^{-1} vs 3.10 Mg ha^{-1}). Similar results were obtained in a study conducted in Syria, where high evapotranspirative demand were recorded, that showed an yield increase of 45 % under irrigation versus rainfed condition (Oweis et al., 2005). No significant differences (Table 5) were observed between ETC and ML-DSS in both years, with 8.90 g plant^{-1} and 9.41 g plant^{-1}, respectively, and 4.42 Mg ha^{-1} and 4.66 Mg ha^{-1}. Regarding the effect of irrigation on DB_{plant}, the Post-hoc Tukey's test (Table 5) showed a significant difference ($p < 0.05$) between irrigation treatments and the rainfed treatment in 2020-21, with the highest values recorded under ML-DSS (average 16.33 g plant^{-1}) and the lowest under rainfed (average 10.26 g plant^{-1}). On the contrary, in 2021-22 the ETC treatments showed, on average, the highest value (10.85 g plant^{-1}) compared to ML-DSS (8.72 g plant^{-1}) and rainfed (7.93 g plant^{-1}). In terms of TDB, significant differences ($p < 0.01$) among the irrigation treatments were recorded only in the first year, where ML-DSS showed the highest values (8.17 Mg ha^{-1}) compared to the ETC and rainfed, which did not show significant differences between each other with values of 6.15 and 5.12 Mg ha^{-1}, respectively.

3.3 Effects of plant density

A significant effect ($p < 0.05$) of plant density was observed on TDB. The positive effect recorded on total dry biomass is explained by the increase in the number of plants m^{-2} rather than by the interaction of plant densities on the amount of biomass, as shown by the lack of effect on DB_{plant} over the two experimental years (Table 4). In the first year, plant density had no significant effect on Y_{plant} and TY. On the contrary, in the second year, which was less favorable for crop growth, plant density had a greater impact ($p < 0.001$) on TY when comparing the three different plant densities (from 2.88 Mg ha^{-1} to 3.63 Mg ha^{-1}and 3.97 Mg ha^{-1} with D40, D50, and D60, respectively) (Table 4 and 5). We observed an decrease in Y_{plant} and an increase in TY as a function of density, based on the overall data for the experimental treatments (Figure 2).

Figure 2.

In detail, in the first year (Table 5), the yield in D50 and D60 was higher compared to D40 by 17 % and 25 % under the ETC; 17 % and 14 % under the ML-DSS; 17 % and 3 % under the rainfed. Similarly, in the second year (Table 5), the increases were 23 % and 32 % under the ETC; 16 % and 31 % under the ML-DSS; 24 % and 6 % under the rainfed. This suggests that under controlled irrigation conditions and with optimized water management, the benefits of higher plant density can be achieved. However, under rainfed conditions, the optimal plant density is D50. In fact, under rainfed condition, higher densities lead to a significant drop in yield, likely due to too much competition for water.

3.4 Effect of interactions (irrigation *vs* plant density)

No significant interaction was found in the first year between irrigation and plant density on yield. In contrast, in the second year, a significant interaction ($p < 0.05$) on yield was observed (Table 4). In particular, we observed that at D40, ETC and ML-DSS significantly differ (3.07 and 3.36 Mg ha^{-1}, respectively); similar results were observed at D60 (4.56 and 4.84 Mg ha^{-1}, respectively) (Figure 2).

On the other hand, no significant differences were recorded at D50 (4.00 and 3.99 Mg ha^{-1}) between ML-DSS and ETC. Finally, all treatments under rainfed conditions differ significantly from irrigated ones with the same plant density: 1.98, 2.40 and 2.02 Mg ha^{-1} at D40, D50 and D60, respectively.

These results suggest that irrigation programmed with a machine learning approach has produced a better response in terms of yield under more difficult meteorological conditions for the plant. This could be achieved by better monitoring of the environmental factors involved, which can predict and reduce water stress for the plant.

3.5 Water productivity

DBWP TYWP, on average, show significant different values depending on the year ($p < 0.001$), irrigation treatment ($p < 0.001$, only for TYWP) and plant density ($p < 0.01$ and $p < 0.05$, respectively). No significant interactions were found between irrigation and plant density (Table 4). In the first year, water productivity indices reached higher values than in the second year (Table 5), with a decrease of TYWP of 31 % for ETC, 38 % for ML-DSS and 62 % for rainfed.

In general, TYWP and DBWP progressively increase with plant density (Table 5). TYWP rises from 6.01 kg ha^{-1} mm^{-1} under D40 to 7.35 kg ha^{-1} mm^{-1} under D50, and 7.50 kg ha^{-1} mm^{-1} under D60. Similarly, DBWP increases from 7.75 kg ha^{-1} mm^{-1} under D40 to 10.51 kg ha^{-1} mm^{-1} under D50, and 11.43 kg ha^{-1} mm^{-1} under D60.

The effect of plant density on TYWP and DBWP differed between irrigated and rainfed treatments (Figure 3). Under irrigation, both TYWP and DBWP increased with plant density. Under rainfed conditions, TYWP decreased significantly, while DBWP still increased with density despite the absence of irrigation. This suggests that under rainfed conditions, the water used for biomass production is at the expense of yield during the critical pod-filling phase.

Figure 3.

This is confirmed by the negative effect of the plant density on HI, observed under rainfed conditions confirms this observation. In general, as reported by Kimbirauskienė et al. (2024) for broad beans, excessively high densities can lead to competition among plants for resources such as water, sunlight, and soil nutrients.

Post Tukey's test (Table 5) reveals no significant differences of water productivity between ETC and ML-DSS (7.57 kg ha^{-1} mm^{-1} *vs* 8.00 kg ha^{-1} mm^{-1}, on average), while the rainfed treatment differed significantly from both irrigated treatments (5.27 kg ha^{-1} mm^{-1}, on average$^{)}$. Similar results were recorded for biomass, where ML-DSS showed the highest value than ETC and rainfed treatment (10.98 kg ha^{-1} mm^{-1}, 9.90 kg ha^{-1} mm^{-1} and 8.82 kg ha^{-1} mm^{-1}, respectively). In the first year, the ML-DSS showed the highest average water productivity (9.71 kg ha^{-1} mm^{-1}) compared to the ETC (9.14 kg ha^{-1} mm^{-1}) and rainfed (6.54 kg ha^{-1} mm^{-1}), which did not differ significantly. In the second year, ETC (6.00 kg ha^{-1} mm^{-1}) and ML-DSS (6.29 kg ha^{-1} mm^{-1}) had comparable TYWP, followed by rainfed (4.01 kg ha^{-1} mm^{-1}).

No significant interaction effect between plant density and irrigation on DBWP and TYWB was observed between the two years (Table 4). In the second year, ML-DSS with D60 achieved the best performances in terms of TYWP (7.52 kg ha^{-1} mm^{-1}), followed by ETC with D60 (7.06 kg ha^{-1} mm^{-1}) (Figure 2). All irrigated treatments differed from the rainfed, except for ETC with D40 (4.75 kg ha^{-1} mm^{-1}), which was comparable to the rainfed treatment at 50 plants m^{-2} (4.66

kg ha^{-1} mm^{-1}). In conclusion, the combination of irrigation and D60 achieved the highest TYWP. Under rainfed conditions, D50 yielded the best TYWP in the second year, reaching 4.66 kg ha^{-1} mm^{-1}.

3.6 Economical profitability

Economic profitability, expressed as GM, varied between the two years. The delta GM for irrigated treatments compared to rainfed one (Δ % rainfed) averaged +42 % in the first year and +27 % in the second year (Table 6). This difference in profitability is attributed to the higher incidence of IWC in the second year (51 %), which did not lead to a significant increase in grain yield.

Table 6.

ML-DSS and ETC showed, on average, similar GEWP in the first year (1.66 € m^{-3} ha^{-1} and 1.65 € m^{-3} ha^{-1}). However, in the second year, ML-DSS had the highest GEWP (0.41 € m^{-3} ha^{-1}) compared to the ETC (0.32 € m^{-3} ha^{-1}) (Table 7).

Table 7.

Economic water productivity dropped significantly in the second year due to high water inputs and low yields. Plant density influenced economic water productivity. In both years, increased plant density improved economic water productivity in terms of GEWP and EWPR, except under ML-DSS in 2020-21. In this case, GEWP declined from 1.90 to 1.68 € m^{-3} ha^{-1}, and EWPR dropped from 7.52 to 7.21 € m^{-3} ha^{-1} when comparing D50 to D60. The study found that, in the first year, irrigation increased GM for all irrigated treatments except for the ETC with D40, which showed GM comparable to the rainfed treatment with D50. In the second year, the ETC at D40 and D50. and ML-DSS at D40 showed GM reductions of 50 %, 1.9 %, and 1.8 %, respectively, compared to the rainfed control. In contrast, all irrigation treatments with D60 achieved significantly higher GM than the rainfed. These findings suggest that under unfavorable meteorological conditions, irrigation, while boosting yield, is not economically viable for broad beans at current market prices.

4. Conclusions

The results of this study underscore the importance of supplemental irrigation in managing the variability of broad bean yields in response to climatic conditions. Differences in production and growth observed across the two years reflected the impact of irrigation, with irrigated treatments consistently outperforming the rainfed condition. A strong positive effect of plant density on total yield was recorded, although under rainfed conditions higher densities reduced yields. The ML-DSS system emerged as the best irrigation management strategy, with average yield increases of 5 % and 42 % over the ETC and rainfed conditions, respectively. Both irrigation strategies yielded the highest production with a density of 60 plants m^{-2}, while under rainfed conditions, broad beans responded optimally to a density of 50 plants m^{-2}. The use of economic efficiency indices for irrigation enables a comparative economic assessment of different irrigation strategies, highlighting potential economic constraints to their adoption. These indices are valuable for quickly identifying situations where supplemental irrigation may not be economically feasible and guiding efforts to enhance the economic productivity of water use. This study acknowledges certain limitations. For the economic analysis, water efficiency indicators would ideally be quantified at the farm level rather than at the field or crop scale. Additionally, expanding the analysis to include a range of pedoclimatic conditions and agricultural systems would provide further insights into the broader applicability and adaptability of irrigation strategies.

References

ARSIAL - Regional Agency for the Development and Innovation of Agriculture in Lazio. (n.d.). SIARL - Integrated Agrometeorological Service of the Lazio Region. Retrieved August 2, 2024, from https://www.arsial.it/siarl-servizio-integrato-agrometeorologico-della-regione-lazio/

Aschi, A., Aubert, M., Riah-Anglet, W., Nélieu, S., Dubois, C., Akpa-Vinceslas, M., & Trinsoutrot-Gattin, I. (2017). Introduction of Faba bean in crop rotation: Impacts on soil chemical and biological characteristics. *Applied Soil Ecology*, 120, 219–228. https://doi.org/10.1016/j.apsoil.2017.08.017.

Attia, M. A. (2013). Effects of supplementary irrigation and bio-fertilization on the yields of faba bean and lentil under rainfed conditions. *American Journal of Plant Sciences, 4*(5), 960-967. https://doi.org/10.4236/ajps.2013.45118

Bąk, B., & Łabędzki, L. (2002). Assessing drought severity with the relative precipitation index and the standardised precipitation index. *Journal of Water and Land Development, 12*(6), 89–105.

Bashir, S. S., Hussain, A., Hussain, S. J., Wani, O. A., Nabi, S. Z., Dar, N. A., Baloch, F. S., & Mansoor, S. (2021). Plant drought stress tolerance: Understanding its physiological, biochemical and molecular mechanisms. *Biotechnology & Biotechnological Equipment*, 35(1), 1912-1925. https://doi.org/10.1080/13102818.2021.2020161.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Chamber of Commerce of Bologna. (2021). *Weekly wholesale price list no. 36 of September 16, 2021*. Bologna, Italy: Chamber of Commerce of Bologna.

Chamber of Commerce of Bologna. (2022). *Weekly wholesale price list no. 36 of September 29, 2022*. Bologna, Italy: Chamber of Commerce of Bologna.

Chammakhi, C., Boscari, A., Pacoud, M., Aubert, G., Mhadhbi, H., & Brouquisse, R. (2022). Nitric oxide metabolic pathway in drought-stressed nodules of faba bean (Vicia faba L.). *International Journal of Molecular Sciences, 23*(21), 13057. https://doi.org/10.3390/ijms23211305.

Consorzio di Bonifica Litorale Nord. (2024). Retrieved from https://www.consorziobonificalitoralenord.it/

De Jong, R., & Zentner, R.P. (1985). Assessment of the SPAW model for semi-arid growing conditions with minimal local calibration. Agricultural Water Management, 10(1), 31-46. https://doi.org/10.1016/0378-3774(85)90033-2

Di Paolo, E., Garofalo, P., & Rinaldi, M. (2015). Irrigation and nitrogen fertilization treatments on productive and qualitative traits of broad bean (Vicia faba var. minor L.) in a Mediterranean environment. *Legume Research, 38*(3), 209-218. https://doi.org/10.18805/lr.v38i3.5540

Di Paolo, E., Rinaldi, M., & Garofalo, P. (2009). Effect of climate change on the growth and productivity of faba bean (Vicia faba var. minor L.) under dryland conditions and supplemental irrigation*. Italian Journal of Agrometeorology*, 2: 68-69.

Donati, I.I.M., Viaggi, D., Srdjevic, Z., Srdjevic, B., Di Fonzo, A., Del Giudice, T., Cimino, O., Martelli, A., Dalla Marta, A., Henke, R., et al. (2023). An analysis of preference weights and setting priorities by irrigation advisory services users based on the analytic hierarchy process. *Agriculture*, 13, 1545. https://doi.org/10.3390/agriculture13081545

Dudek, S., Kuśmierek-Tomaszewska, R., & Żarski, J. (2018). Forecasting production effects of irrigated faba bean (Vicia faba var. minor) depending on drought levels. *Research for Rural Development*, 24, 77-82. Latvia University of Life Sciences and Technologies.

Fang, Z., Chen, Y., Zhang, J., Zhang, Y., & Sun, J. (2023). Climate change affects seed germination and seedling growth of common bean (Phaseolus vulgaris L.) under different light conditions. *Frontiers in Plant Science*, 14, Article 1236147. https://doi.org/10.3389/fpls.2023.1236147.

FAO. (2002). Deficit irrigation practices. *FAO Water Reports 22*. Food and Agriculture Organization of the United Nations, Rome. Available at: http://www.fao.org/3/y3655e/y3655e00.htm

Fernández, J. E., Alcon, F., Diaz-Espejo, A., Hernandez-Santana, V., & Cuevas, M. V. (2020). *Water use indicators and economic analysis for on-farm irrigation decision: A case study of a super high-density olive tree orchard*. *Agricultural Water Management, 237*, Article 106074. https://doi.org/10.1016/j.agwat.2020.106074

Gatta, D., Russo, C., Giuliotti, L., Mannari, C., Picciarelli, P., Lombardi, L., Giovannini, L., Ceccarelli, N., & Mariotti, L. (2013). Influence of partial replacement of soya bean meal by faba beans or peas in heavy pigs' diet on meat quality, residual anti-nutritional factors and phytoestrogen content. *Archives of Animal Nutrition, 67*(3), 235-247. https://doi.org/10.1080/1745039X.2013.801137

Karkanis, A., Ntatsi, G., Lepse, L., Fernández, J. A., Vågen, I. M., Rewald, B., Alsiņa, I., Kronberga, A., Balliu, A., Olle, M., Bodner, G., Dubova, L., Rosa, E., & Savvas, D. (2018). Faba Bean Cultivation – Revealing Novel Managing Practices for More Sustainable and Competitive European Cropping Systems. *Frontiers in Plant Science*, 12, 614907.

https://doi.org/10.3389/fpls.2021.614907

Katerji, N., Mastrorilli, M., Lahmer, F. Z., Maalouf, F., & Oweis, T. (2011). Faba bean productivity in saline-drought conditions. *European Journal of Agronomy, 35*(1), 2-12. https://doi.org/10.1016/j.eja.2011.03.001.

Kimbirauskienė, R., Sinkevičienė, A., Švereikaitė, A., & Romaneckas, K. (2024). The complex effect of different tillage systems on the Faba bean agroecosystem. *Plants, 13*, 513. https://doi.org/10.3390/plants13040513

Kumari, S., Sehgal, A., Hanumantharao, B., Nair, R. M., Vara Prasad, P. V., Kumar, S., Gaur, P. M., Farroq, M., Siddique, K. H. M., & Kumar, A. (2017). Food legumes and rising temperatures: Effects, adaptive functional mechanisms specific to reproductive growth stage, and strategies to improve heat tolerance. *Frontiers in Plant Science*, 8, 1658. https://doi.org/10.3389/fpls.2017.01658.

Lenth, R. V. (2022). *emmeans*: Estimated marginal means, aka least-squares means. R package version 1.7.2.

Lorite, I.J., García-Vila, M., Carmona, M.A., Santos, C., & Soriano, M.A. (2012). Assessment of the irrigation advisory services' recommendations and farmers' irrigation management: A case study in Southern Spain. *Water Resources Management, 26*, 2397–2419. https://doi.org/10.1007/s11269-012-0023-3

Luikham, E., Phulchand, M., & Anal, P. S. M. (2009). Response of broad bean (Vicia faba L.) to row spacing and phosphorus under late sown rainfed conditions of Manipur. *Agricultural Science Digest, 29*(1), 54-56. https://doi.org/10.18805/ag.RF59

Marrou, H., Ghanem, M. E., Sadoun, S. B., Kibbou, F., Amri, M., Maalouf, F., & Sinclair, T. R. (2021). Restrictive irrigation improves yield and reduces risk for faba bean across the Middle East and North Africa: A modeling study. *Field Crops Research, 262*, 108029.

Meng, Z., Liu, Q., Zhang, Y., Chen, J., Sun, Z., Ren, C., Zhang, Z., Cheng, X., & Huang, Y. (2021). Nutritive value of faba bean (Vicia faba L.) as a feedstuff resource in livestock nutrition: A review. *Food Science & Nutrition*, 9(9), 5244–5262. https://doi.org/10.1002/fsn3.2342.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., & Kijne, J. (2007). Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management, 89*(1-2), 1-8. https://doi.org/10.1016/j.agwat.2007.01.002

Morris, J., Ahodo, K., Weatherhead, E. K., Daccache, A., Patel, A., & Knox, J. W. (2014). Economics of rainfed and irrigated potato production in a humid environment. Economics of water management in agriculture, 71-97 ISBN 9780429067730

Mwanamwenge, J., Loss, S., Siddique, K., & Cocks, P. (1999). Effect of water stress during floral initiation, flowering and podding on the growth and yield of faba bean (Vicia faba L.). *European Journal of Agronomy, 11*(1), 1-11. https://doi.org/10.1016/S1161-0301(99)00003-9.

Nangia, V., Oweis, T. (2016). Supplemental Irrigation: A Promising Climate-resilience Practice for Sustainable Dryland Agriculture. In: Farooq, M., Siddique, K. (eds) Innovations in Dryland Agriculture. *Springer*, Cham. https://doi.org/10.1007/978-3-319-47928-6_20

Ouji, A., Naouari, M., Mouelhi, M., & Ben Younes, M. (2017). Yield and yield components of faba bean (Vicia faba L.) as influenced by supplemental irrigation under semi-arid region of Tunisia. *American Journal of Agriculture and Forestry*, 5(5), 187-192. https://doi.org/10.11648/j.ajaf.20170505.12.

Oweis, T., Hachum, A., & Pala, M. (2005). Faba bean productivity under rainfed and supplemental irrigation in northern Syria. *Agricultural Water Management*, 73(1), 57–72. https://doi.org/10.1016/j.agwat.2004.09.022

Oweis, T., Zhang, H., & Pala, M. (1999). Water use efficiency of rainfed and irrigated bread wheat in a Mediterranean environment. *Agricultural Water Management, 42*(3), 241–255.

Pang, H., Lian, Y., Zhao, Z., Guo, H., Li, Z., Hu, J., ... & Wang, Z. (2024). Compensatory effect of supplementary irrigation on winter wheat under warming conditions. *Agricultural Water Management*, 295, 108778 https://doi.org/10.1016/j.agwat.2024.108778Pereira, L.S., Cordery, I., & Iacovides, I. (2012). Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agricultural Water Management, 108*, 39–51. https://doi.org/10.1016/j.agwat.2011.08.022

Perelli, C., Branca, G., Corbari, C., & Mancini, M. (2024). Physical and economic water productivity in agriculture between traditional and water-saving irrigation systems: A case study in Southern Italy. *Sustainability, 16*(12), Article 4971. https://doi.org/10.3390/su16124971

Rey, D., Holman, I. P., Daccache, A., Morris, J., Weatherhead, E. K., & Knox, J. W. (2016). Modelling and mapping the economic value of supplemental irrigation in a humid climate. *Agricultural Water Management*, 173, 13-22 https://doi.org/10.1016/j.agwat.2016.04.017

Santini, A., Di Fonzo, A., Giampietri, E., Martelli, A., Cimino, O., Dalla Marta, A., Annosi, M.C., Blanco-Velázquez, F.J., Del Giudice, T., & Altobelli, F. (2023). A step toward water use sustainability: Implementing a business model canvas for irrigation advisory services. *Agriculture, 13*, 1081. https://doi.org/10.3390/agriculture13051081

Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, 52(3/4), 591-611.

Toffanin, A., Maucieri, C., Rossi, G., Paulon, G., Trestini, S., & Borin, M. (2023). Does drip irrigation contribute to the economic sustainability of soybean production? *Italian Journal of Agrometeorology* (2): 21-31. doi: 10.36253/ijam-2318

Torres, M. D. O., Howitt, R., & Rodrigues, L. N. (2016). Modeling the economic benefits and distributional impacts of supplemental irrigation. *Water Resources and Economics*, 14, 1-12 https://doi.org/10.1016/j.wre.2016.03.001

Umutoni, L., & Samadi, V. (2024). Application of machine learning approaches in supporting irrigation decision making: A revew. Agricultural Water Management, 271, 108710. https://doi.org/10.1016/j.agwat.2024.108710

Vico, G., & Porporato, A. (2011). From rainfed agriculture to stress-avoidance irrigation: II. Sustainability, crop yield, and profitability. *Advances in Water Resources, 34*(2), 272–281. https://doi.org/10.1016/j.advwatres.2010.11.011

Wichelns, D. (2002). An economic perspective on the potential gains from improvements in irrigation water management. *Agricultural Water Management*, 52(3), 233–248. https://doi.org/10.1016/S0378-3774(01)00134-2

El Chami, D., Knox, J.W.,Daccache, A., Weatherhead, E.K. (2015).The economics of irrigating wheat in a humid climate – A study in the East of England, *Agricultural Systems*, Volume 133, 97-108, ISSN 0308-521X, https://doi.org/10.1016/j.agsy.2014.11.001.

Yazar, A., Mart, D., Bozkurt Çolak, Y., & İnce Kaya, Ç. (2017). Yield Response of Faba Bean to Various Irrigation Strategies in the Mediterranean Region. *International Journal of Research in Agriculture and Forestry*, 4 (7), 9-19, https://doi.org/10.1016/j.agwat.2018.12.023Zeleke, K., &

Zeleke, K., & Nendel, C. (2019). Growth and yield response of faba bean to soil moisture regimes and sowing dates: Field experiment and modelling study. *Agricultural Water Management*, 242, 106376.

Tables:

Table 1. Main soil chemical and physical properties of the experimental field

Parameter	**Unit of measurement**	**Value**
pH		7.00
EC $_{[1:2]}$	mS cm^{-1} at 25 °C	0.21
Salt	‰	0.30
Total N [Kjeldahl method]	N g kg^{-1}	1.50
Avaible P [Olsen method]	P_2O_5 mg kg^{-1}	36.00
Exchangeable K [$BaCl_2$ method]	K_2O mg kg^{-1}	478.00
Organic Matter [Walkley-Black method]	%	2.61
C/N		10.10
CEC [$BaCl_2$ method]	cmol(+) kg^{-1}	23.00
Sand [USDA method]	%	23.20
Clay [USDA method]	%	41.00
Silt [USDA method]	%	35.80
Field capacity (-0,03 MPa) [*]	% vol	30.48
Wilting point (-1.5 MPa) [*]	% vol	13.27
Bulk density	t m^{-3}	1.27

Note: [*] Soil-Plant-Atmosphere-Water software developed by USDA (Jong and Zentner, 1985)

Table 2. Annual weather data of experimental site during the two crop seasons

	Nov.	Dec.	Jen.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Annual
					Year 2020/21					
Temperature mean [°C]	10.8	7.0	6.0	9.1	9.2	10.8	15.6	20.5	23.4	12.4
Average Max. [°C]	12.6	10.0	8.5	12.3	14.1	17.0	20.5	25.5	27.4	16.4
Average Min. [°C]	9.0	4.0	3.5	6.0	4.3	4.6	10.8	15.5	19.4	8.5
Precipitation [mm]	15.8	61.0	87.4	56.0	30.4	79.2	24.8	49.6	4.6	408.8
Cumulative monthly ET_0 [mm]	12.6	23.0	48.7	83.2	148.9	227.8	339.0	480.2	616.7	616.7
RPI *	-90 %	-31 %	-2 %	-45 %	-70 %	34 %	-65 %	-77 %	-87 %	-44 %
					Year 2021/22					
Temperature mean [°C]	11.7	7.3	5.2	7.1	9.5	12.0	17.7	24.3	27.9	13.6
Average Max. [°C]	17.2	13.9	12.9	12.7	15.4	19.4	26.8	30.3	34.4	20.3
Average Min. [°C]	6.7	1.5	-0.6	1.9	2.4	4.0	9.3	18.5	21.3	7.2
Precipitation [mm]	267	83.4	33.4	39.8	20.2	26.2	4.4	1.6	0.8	476.8
Cumulative monthly ET_0 [mm]	38.7	67.2	100.8	139.1	214.8	325.6	496.3	666.6	843.0	843.0
RPI *	75 %	-6 %	-62 %	-61 %	-80 %	-57 %	-94 %	-94 %	-98 %	-34 %

***Note: RPI: Relative Precipitation Index**

Table 3. Number of irrigations and total water applied (mm) in 2021 and 2022.

Irrigation treatment	Number of irrigations	Total irrigation water (mm)	Irrigation season
2020-21			
ETC	2	48	From 18 May to 20 May
ML-DSS	5	52	From 14 March to 23 May
2021-22			
ETC	3	150	From 9 March to 23 May
ML-DSS	6	143	From 3 March to 29 May

Table. 4 Analysis of variance for the yield and growth parameters. Y: year; T: irrigation treatments; D: plant density; Y_{plant}: yield per plant; TDB: total dry biomass; TY: total yield; DB_{plant}: dry biomass per plant; HI: harvest index; DBWP: dry biomass water productivity; TYWP: total yield water productivity.

	Y_{plant}	TY	TDB	DB_{plant}	Stems lenght	HI	DBWP	TYWP
Y	***	***	***	***	"."	*	***	***
				Year 2021				
T	*	**	**	*	"."	**	**	*
D	ns	ns	**	ns	ns	**	**	ns
T x D	ns	ns	ns	ns	ns	ns	ns	ns
				Year 2022				
T	***	***	"."	***	ns	**	ns	***
D	ns	***	*	ns	ns	ns	*	**
T x D	ns	*	ns	ns	ns	ns	ns	"."

*** $p < 0.001$; ** $p < 0.01$: * $p < 0.05$

Table 5. Post-hoc Tukey´s pairwise comparison test for different crop parameters and factors of study by irrigation treatments and plant density. ET_c: crop evapotranspiration; ML-DSS: machine learning decision support system; Y_{plant}: yield per plant; TDB: total dry biomass; TY: total yield; DB_{plant}: dry biomass per plant; HI: harvest index; DBWP: dry biomass water productivity; TYWP: total yield water productivity.

	Y_{plant} (g)	TY (Mg ha^{-1})	TDB (Mg ha^{-1})	DB_{plant} (g)	Stems lenght (cm)	HI	DBWP (kg ha^{-1} mm^{-1})	TYWP (kg ha^{-1} mm^{-1})
Year 2021								
Irrigation Treatment								
ETC	9.70 ab	4.80 a	6.15 b	12.26 ab	95.15	0.44 a	11.70 b	9.14 ab
ML-DSS	10.35 a	5.10 a	8.17 a	16.33 a	102.30	0.39 b	15.50 a	9.71 a
Rainfed	6.54 b	3.19 b	5.12 b	10.27 b	94.22	0.39 b	10.50 b	6.54 b
Plant density								
40 plants m^{-2}	9.69	3.87	5.02 b	12.55	94.19	0.44 a	9.74 b	7.51
50 plants m^{-2}	9.24	4.60	6.87 a	13.73	97.85	0.40 ab	13.36 a	8.92
60 plants m^{-2}	7.69	4.62	7.55 a	12.58	99.64	0.39 b	14.63 a	8.94
Year 2022								
Irrigation Treatment								
ETC	8.07 a	4.03 a	5.44	10.85 a	97.26	0.43 b	8.10	6.00 a
ML-DSS	8.48 a	4.23 a	4.30	8.72 a	96.11	0.50 a	6.41	6.29 a
Rainfed	4.55 b	2.23 b	3.98	7.93 b	93.05	0.36 c	7.14	4.01 b
Plant density								
40 plants m^{-2}	7.22	2.88 b	3.64 b	9.11	94.28	0.43	5.75 b	4.50 b
50 plants m^{-2}	7.27	3.63 a	4.92 a	9.75	98.31	0.42	7.80 a	5.68 a
60 plants m^{-2}	6.62	3.97 a	5.15 a	8.61	93.82	0.83	8.09 a	6.13 a
All years								
Irrigation Treatment								
ETC	8.90 a	4.42 a	5.79 a	11.56 ab	96.20	0.44 a	9.90	7.57 a
ML-DSS	9.41 a	4.66 a	6.24 a	12.53 a	99.21	0.45 a	10.98	8.00 a
Rainfed	5.54 b	2.71 b	4.55 b	9.11 b	93.61	0.38 b	8.82	5.27 b
Plant density								
40 plants m^{-2}	8.45	3.38 b	4.33 b	10.83	94.20	0.44	7.75 b	6.01 b
50 plants m^{-2}	8.24	4.12 ab	5.82 a	11.64	97.40	0.42	10.51 a	7.35 a
60 plants m^{-2}	7.15	4.29 a	6.42 a	10.70	97.30	0.41	11.43 a	7.50 a

NOTE: If two or more means share the same grouping symbol then we cannot show them to be different. But we also did not show them to be the same.

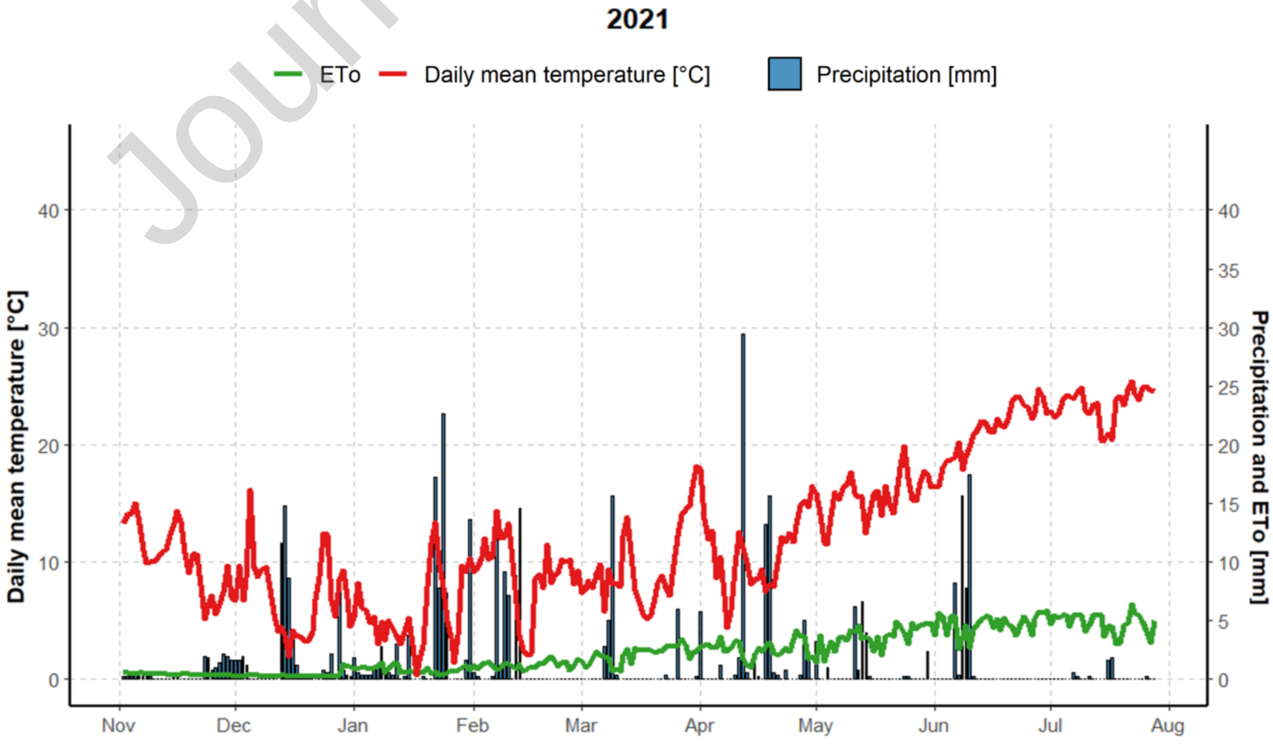
Table 6. Average gross margin (€ ha^{-1}) of Irrigated and Rainfed treatments in 2021 and 2022 experimental years and Incidence of water costs. GM: gross margin; IWC: incidence of water cost.

Year	GM irrigated (€ ha^{-1})	GM rainfed (€ ha^{-1})	IWC	Δ % rainfed	Δ € rainfed
2021	831.00 €	487.33 €	26%	42 %	343.70 €
2022	535.10 €	389.87 €	51 %	27 %	145.23 €

Table 7. Gross economic water productivity (GEWP), economic water productivity ratio (EWPR), gross margin (GM) and incidence of water cost (IWC) grouped by irrigation treatments and plant density

	2020-21				2021-22			
	GEWP (€ m^{-3} ha^{-1})	**EWPR (€)**	**GM (€ ha^{-1})**	**IWC (%)**	**GEWP (€ m^{-3} ha^{-1})**	**EWPR (€)**	**GM (€ ha^{-1})**	**IWC (%)**
ETC								
40 plants m^{-2}	1.31	6.23	630.00	27	0.11	1.99	162.74	54
50 plants m^{-2}	1.82	7.52	871.00	26	0.36	2.59	533.00	52
60 plants m^{-2}	1.87	7.83	896.00	24	0.49	2.95	738.00	50
ML-DSS								
40 plants m^{-2}	1.39	6.22	723.90	29	0.23	2.28	322.00	52
50 plants m^{-2}	1.90	7.52	989.00	27	0.39	2.71	560.00	51
60 plants m^{-2}	1.68	7.21	875.20	26	0.62	3.28	893.00	49
Rainfed								
40 plants m^{-2}	-	-	453.00	0	-	-	328.00	0
50 plants m^{-2}	-	-	610.00	0	-	-	543.00	0
60 plants m^{-2}	-	-	397.00	0	-	-	297.84	0

Caption Figures:



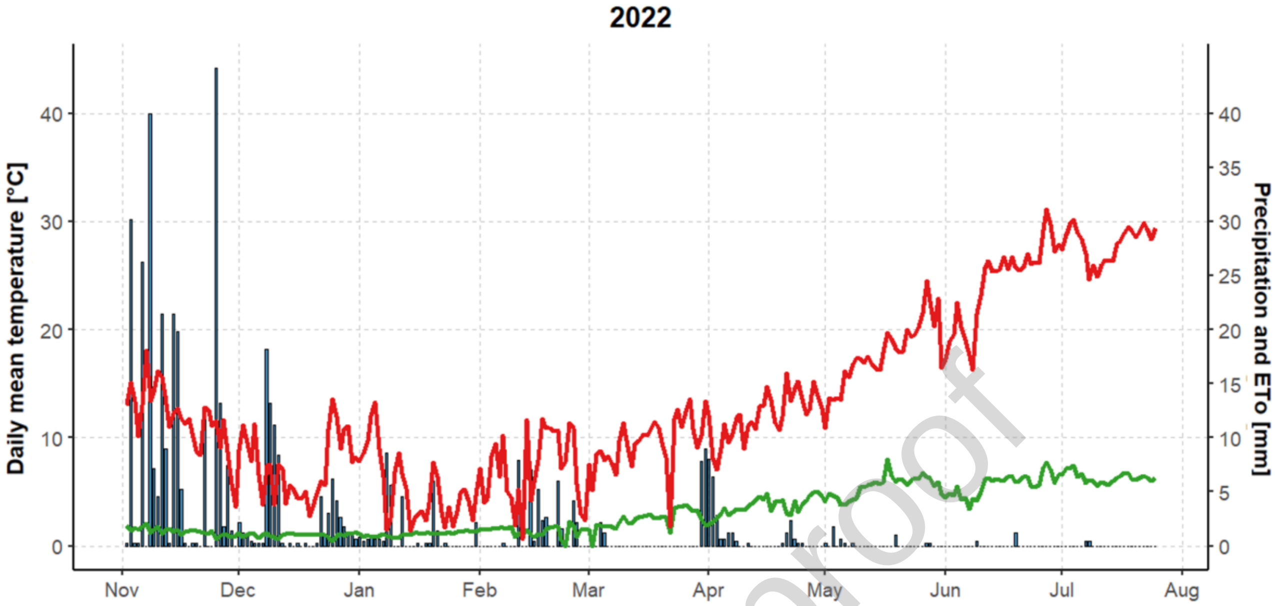
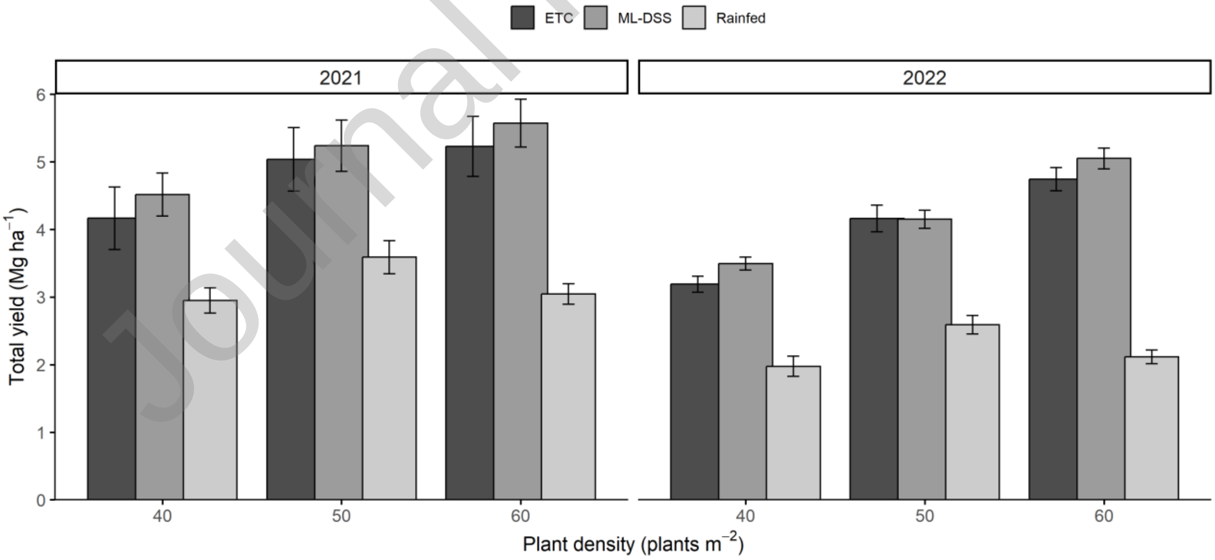


Figure 1. Mean daily temperatures, ET_0 and rainfall in the two years of the experiment



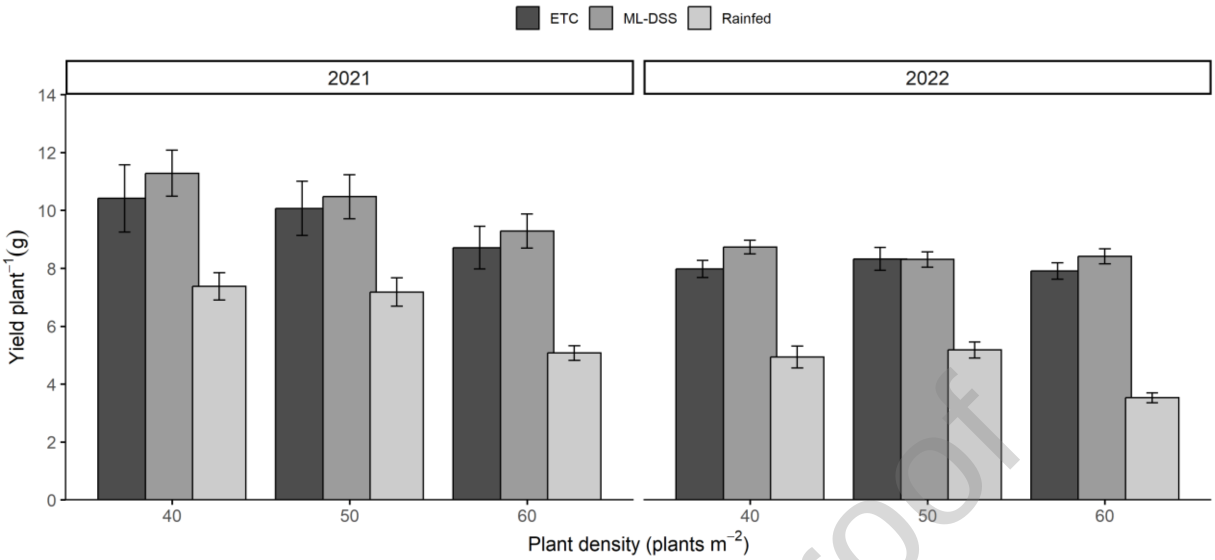
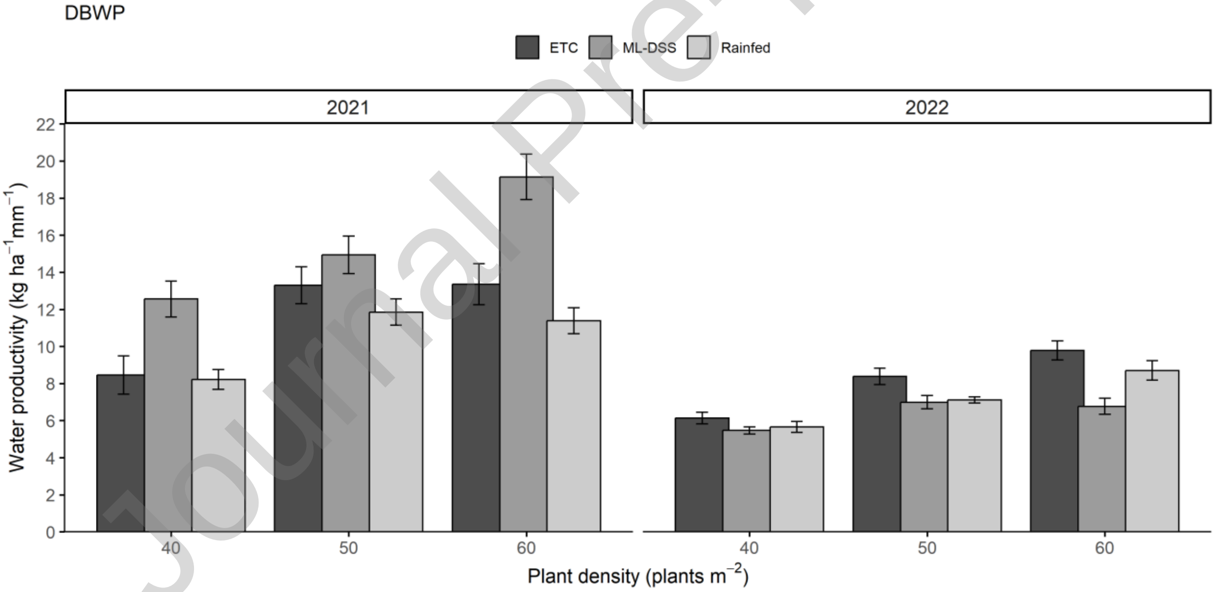


Figure 2. Total yield (Mg ha^{-1}) and yield plant^{-1} (g) grouped by year, irrigation treatment and plant density (plants m^{-2})



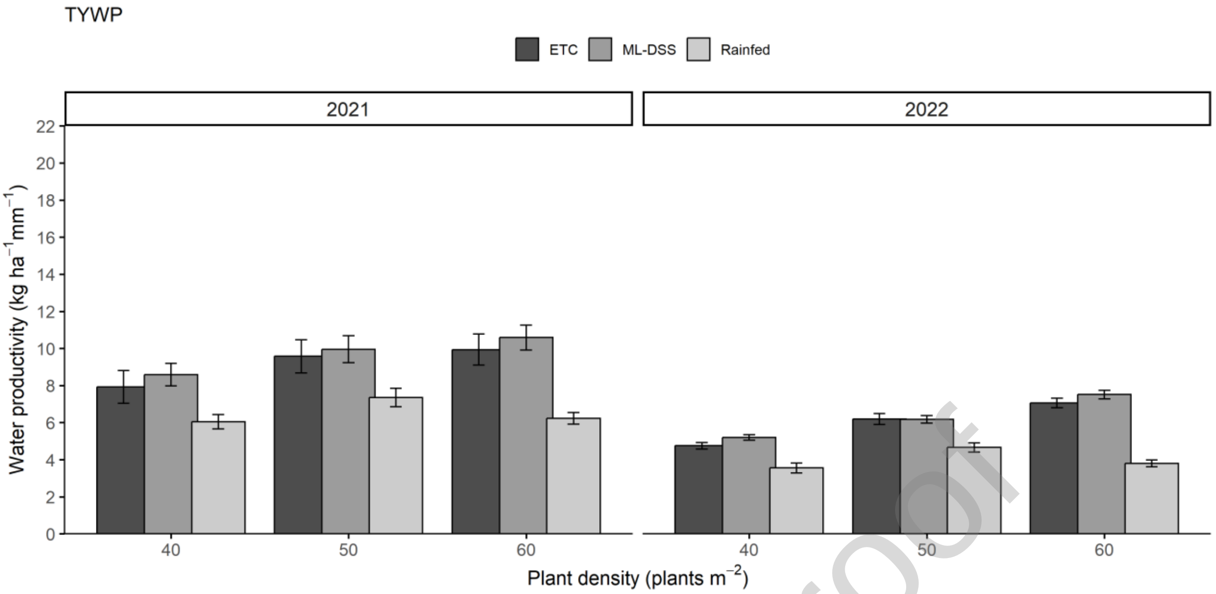


Figure 3. Dry biomass water productivity (DBWP, kg ha^{-1} mm^{-1}) and total yield water productivity (TYWP, kg ha^{-1} mm^{-1}) grouped by year, irrigation treatment and plant density (plants m^{-2})

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: