Italian Journal of
Agrometeorology
Rivista Italiana di Agrometeorologia

Firenze University Press
www.fupress.com/ijam

Citation: 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

Received: September 19, 2023

Accepted: November 25, 2023

Published: January 20, 2024

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

ORCID:

AT: 0000-0001-9879-3149
CM: 0000-0003-4004-6612
ST: 0000-0002-9828-8262
MB: 0000-0002-4074-2098

Does drip irrigation contribute to the economic sustainability of soybean production?

Arianna Toffanin[1], Carmelo Maucieri[2,*], Giampaolo Rossi[1], Graziano Paulon[1], Samuele Trestini[3], Maurizio Borin[2]

[1] *Consorzio di Bonifica Veneto Orientale (CBVO) – Piazza Indipendenza 25, 30027 – San Donà di Piave (VE), Italy*
[2] *Department of Agronomy Food Natural resources Animals and Environment — DAFNAE, University of Padova, Agripolis Campus, Viale dell'Università 16, 35020 – Legnaro (PD), Italy*
[3] *Department of Land, Environment, Agriculture and Forestry — TESAF, University of Padova, Agripolis Campus, Viale dell'Università 16, 35020 – Legnaro (PD), Italy*
*Corresponding author. E-mail: carmelo.maucieri@unipd.it

Abstract. A two-year (2020, 2022) field experiment on soybean was conducted in northeaster Italy to evaluate the effect of irrigation (drip irrigation *vs*. rainfed), soil amendment (compost *vs*. digestate) and a cover crop (triticale *vs*. no cover crop) on grain yield and quality. Highly different rainfall amounts (627 mm and 258 mm in 2020 and 2022, respectively) and similar ET0 (578 mm and 581 mm in 2020 and 2022, respectively) were recorded during the growing seasons. Irrigation was managed using the web platform Irriframe suppling 51 mm in 2020 and 157 mm in 2022. Irrigation was the only experimental factor with significant effects on soybean grain yield and quality, except soil amendment on aboveground biomass production. In 2020, drip irrigation had no significant effect on grain yield (4.6 Mg ha^{-1} on average), while it increased it by 157% in 2022 compared to the rainfed control (1.0 Mg ha^{-1}). The grain protein content was reduced by irrigation (43.2 ± 1.3% and 42.6 ± 0.9% under rainfed and irrigation managements, respectively). No treatment effect was observed on the grain oil content. A positive effect of irrigation was observed on water use efficiency, with values ranging from 0.40 ± 0.19 kg m^{-3} to 0.71 ± 0.12 kg m^{-3}. The balance of the economic sustainability of drip irrigation was negative in both years: this irrigation method was not sustainable for soybean within the economic framework of the study area at the time. However, the results also confirmed that irrigation is a key agronomic technique to reduce production variability and dryland vulnerability of soybean.

Keywords: *Glycine max* L., drip irrigation, economic sustainability, soil organic amendment, cover crop, grain yield.

1. INTRODUCTION

Climate change is causing a shift in the distribution and quantity of precipitations, with an increase of the intensity and frequency of extreme events (droughts and floods). Variability in precipitations is occurring at both intraannual and inter-annual levels. This variability has a strong impact on the agricultural sector (Todorović et al., 2021; Ehsan et al., 2022), especially for herbaceous crops with a spring-summer cycle that are cultivated in areas where rainfall used to almost fully meet the crop's evapotranspiration demand. In this context, irrigation is now an indispensable agronomic technique to achieve sustainable yield levels (Tran et al., 2020).

The accessibility of water resources for human uses (household, industrial, agricultural, etc.) is highly dependent on their spatio-temporal distribution and the spatial water balance (Milly et al., 2005; Oki and Kanae, 2006; Konapala et al., 2020). As a result, ongoing climate change may severely reduce the volumes of available water, with a spectacular increase of competition among the various sectors of use (drinking, industrial, and agricultural). Considering that the agricultural sector is the largest user of the water resource (about 70% of all freshwater withdrawals; Wisser et al., 2008), greater efforts are required to reduce the volumes being used. This can be pursued at several scales – from the territorial to the farm scale – through efficient distribution networks managed by Reclamation Consortia at the territorial scale, and by adopting irrigation systems characterized by low irrigation volumes and high irrigation efficiency at the farm scale. Among irrigation systems, drip irrigation has also been proposed for open-field herbaceous crops. This technique offers a number of advantages over traditional irrigation systems (Lamm, 2002; Shahrokhnia and Zare, 2022), chief among them the supply of small volumes of water directly to the root zone of the crop, under the canopy. This minimizes evaporation losses from the soil and increases water use efficiency (WUE). Its adoption has to be supported by good economic results. At present, only few studies conducted in particular contexts have been published, and have given contrasting indications (Narayanamoorthy, 1997; Maisiri et al., 2005; Möller and Weatherhead, 2007; Khor and Feike, 2017). Therefore, the economic impact of drip irrigation should be further analyzed.

Soybean (*Glycine max* L.) is the fourth most widespread crop worldwide (FAOSTAT, 2021). It provides more than 25% of total proteins for human and animal feed, and its global production increased about 13-fold between 1961 and 2017 (Liu et al., 2020). It is a spring-summer crop characterized by high water requirements that can exceed 600 mm. It is frequently grown in rainfed conditions, but it also greatly benefits from irrigation, especially in light of climate change (Karges et al., 2022). In Italy, soybean is cultivated on about 324,000 ha, 40% of which in the Veneto Region, where this study was conducted (ISTAT, 2023).

The Living Labs (LL), a collaborative and user-centred open innovation approach (Beaudoin et al., 2022), has been applied to design the experiment. In the experimental area soybean is irrigated on about 16,000 ha, served by the Veneto Orientale Reclamation Consortium (CBVO). Farmers together with CBVO developed a strong interest on drip irrigation, to manage the open-field summer season herbaceous crops (corn and soybean), soil organic amendment and cover crop introduction in the crop rotation. In this frame an *On-Farm Experimentation* (OFE) has been set up to evaluate the effect of drip irrigation and its interaction with soil organic amendment and the use of cover crops (CC) on the yield, quality and economic performance of soybean.

2. MATERIALS AND METHODS

2.1. Experimental site

The on-farm experimentation was conducted at the "Podere Fiorentina" of the CBVO located in San Donà di Piave (45°38'13.10"N, 12°35'55.00"E, 1 m a.s.l.) during the 2020 and 2022 soybean growing seasons. The area falls into the Cfa climatic class (Köppen's classification), with rainfall mainly in spring and autumn, and frequent thunderstorms in hot and humid summers. Climate data collected by the Veneto Regional Agency for Environmental Protection (ARPAV) from 1992 to 2022 show an average annual rainfall of 966 mm and an average temperature of 13.7 °C (with average maximum and minimum temperatures of 19.1 °C and 8.9 °C, respectively); the mean ET0 is higher than rainfall from June to August.

2.2. Experimental layout

The experimental area covered 4.85 ha, and the layout included 8 plots of 0.3 to 0.9 ha (Figure 1). The studied variables were i) irrigation: drip irrigation (I) *vs.* no irrigation (R); ii) soil amendment: compost from pruning waste (C) *vs.* digestate solid fraction from anaerobic digestion of manure (D); iii) presence (CC - x *triticosecale*) or absence (No CC) of a CC during the winter period.

The soil was characterized by a sandy clay loam texture (USDA classification). Table 1 summarizes its main physical and hydrological characteristics obtained from 54 uniformly distributed sampling points in the experimental area. As showed by the low standard deviation, the soil profile was pretty uniform. We noted a low transversal variability and in view of this, the sub-plots (paragraph 2.3) were distributed along the longitudinal

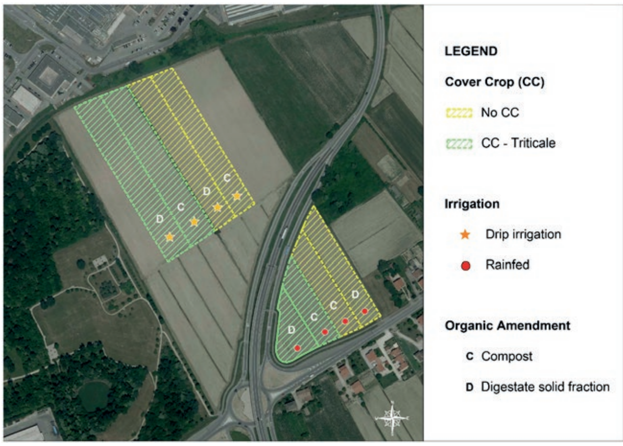

Figure 1. Experimental layout: eight plots with a combination of irrigation (drip irrigation *vs.* rainfed), cover crops (triticale *vs.* no CC), and organic amendments (compost *vs.* digestate solid fraction).

Table 1. Soil physical characteristics and hydrological properties (0-0.40 m depth) (average ± SD).

Variable	Value
Clay (%)	24.7 ± 3.4
Silt (%)	25.1 ± 2.3
Sand (%)	50.2 ± 5.4
Bulk density (Mg m^{-3})	1.26 ± 0.09
Field capacity (% v/v)	27.3 ± 2.1
Wilting point (% v/v)	8.3 ± 2.0

transect of each main plot to represent all the spatial variability of the experimental site.

Soybean (Group 1) was sown on May 9th 2020 and May 11th 2022 with an interrow of 0.75 m, and harvested on October 19th 2020 and October 7th 2022. The organic amendments (together with the CC or weed biomass) were incorporated into the soil by plowing (0.30 m depth) carried out one week before sowing and followed by harrowing for seedbed preparation. The organic matrices were supplied yearly; their dry matter and OC content are reported in Table 2.

Soybean irrigation was carried out through surface drip irrigation by positioning one polyethylene drip line every two soybean rows (distance between two drip lines = 1.5 m) (Figure 2). The drip lines (16 mm diameter) had in-line drippers inserted along the pipe at 0.5 m spacing, with a discharge of 1.1 L h^{-1}. Irrigation was managed through the IRRIFRAME platform, which is a decision support system that integrates cloud data obtained from different sources (meteorological, farm and GIS data) in a water balance model set to simulate the soil water content at different soil depths. The irrigation volumes are reported in Table 3. Weeds were controlled chemically during the growing seasons.

Table 2. Composition of compost and digestate solid fraction in each 2020 and 2022.

Year	Amendment	Quantity supplied (Mg ha^{-1})[1]	Dry Matter (% DM)	Organic Carbon (% DM)
2020	Compost	39.7	71.0	29.0
	Digestate	20.2	23.1	52.8
2022	Compost	43.1	55.4	31.0
	Digestate	21.6	20.2	52.8

[1] Fresh weight.

Figure 2. Installation and layout of drip lines.

2.3. Soybean sampling and analysis

Soybean was sampled at harvest from three permanent 4 m^2 sub-plots *per* plot by measuring total aerial biomass and grain yield. The sub-plots were distributed along a longitudinal transect at regular intervals from the field borders and between two consecutive fields; they were identified with the only purpose of sampling but were managed with the same field operation occurring in the relative field (Giannini et al., 2023). The dry matter content of the two fractions was determined in a thermoventilated oven at 65 °C. The oil and protein contents of soybean grains were determined by NIRS technology (Infratec-1241, Foss Analytical, Hillerød, Denmark).

The harvest index (HI) was calculated after grain yield and aerial biomass determination, using the following equation:

$$HI = \frac{Grain\ yield}{(Grain\ yield + Aboveground\ biomass)}$$

Water use efficiency (WUE) was calculated using the following equation:

$$WUE\ (kg\ mm^{-1}) = \frac{Grain\ yield}{(Rainfall + Irrigation)}$$

2.4. Meteorological data

Meteorological data and reference evapotranspiration (ET0), calculated by the FAO Penman Montieth equation (Allen et al., 1998), were acquired from the Noventa di Piave regional weather station belonging to ARPAV, located about 5 km from the experimental site. Considering the rain variability during the spring-summer season, the rain volume was measured with a rain gauge positioned within the experimental site.

The thermal sum was calculated as growing degree days (ΣGDD) for the whole growing season, using the following equation:

$$GDD = [(T_{max} + T_{min})/2\ ] - T_{base}$$

Where T_{base} is the temperature below which the growing process does not progress, set at 7 °C (Boote et al., 1998). GDD was set at 0 when $[(T_{max}+T_{min})/2]$ was lower than T_{base}. When T_{max} was higher than the optimal temperature (35 °C) (Boote et al., 1998), it was set at 35 °C.

2.5. Economic profitability of irrigation

The contribution of drip irrigation to economic sustainability was assessed using an approach of marginal profitability introduced by the innovation and by applying the following formula:

Irrigation marginal profitability (€ ha^{-1}) = Δ*revenue* – *Irrigation costs*

Where Δ*revenue* (€ ha^{-1}) was calculated as follows:

[*Grain yield with irrigation* (Mg ha^{-1}) – *Grain yield rainfed* (Mg ha^{-1})] * *Grain value* (€ Mg^{-1})

using a grain value of 385,00 € Mg^{-1} in 2020 and 610,50 € Mg^{-1} in 2022, as in the official price list of commodities exchange of Bologna.

The irrigation costs were calculated considering the depreciation costs of durable components [(pump 7,500.00 € and filter 8,000.00 € with a depreciation time of 10 years) + (other system components 4,000.00 € with a depreciation time of 5 years)], the direct costs for the purchase of irrigation equipment (drip lines) (350.00 € ha^{-1} in 2020; 740.00 € ha^{-1} in 2022) and fuel needed for the engine used to put the drip irrigation system under pressure (10.00 € ha^{-1} in 2020; 40.00 € ha^{-1} in 2022) as retrieved from a market survey, equipment and labor needed to set up and remove the irrigation system (115.00 € ha^{-1}), and the costs of labor during the irrigation season (0.25 h ha^{-1} equal to 2.50 € ha^{-1} for each irrigation event).

2.6. Statistical and data analysis

The variables were statistically analyzed by three-way ANOVA with irrigation, soil amendment and cover crop presence as experimental variables. Prior to the ANOVA, data were checked for normality by Shapiro-Wilk test and equal variance test. All statistical analyses were performed using R software (R Core Team, 2021) with the emmeans package for *post-hoc* comparisons (Lenth, 2021) at $p < 0.05$.

The variability of the effects of irrigation, costs and product prices observed during the two years was used to simulate different economic scenarios.

Table 3. Number of irrigation events and total volumes applied (mm) in 2020 and 2022.

Year	Number of irrigation events	Total irrigation volume (mm)	Irrigation season
2020	3	51	6 days (from July 24^{th} to July 31^{st})
2022	20	157	51 days (from June 20^{th} to August 10^{th})

3. RESULTS

3.1. Meteorological conditions and irrigation management

The two seasons showed a similar trend in air temperature, with maximum values recorded in July and August (Figure 3). However, different absolute values were measured. The monthly average temperature was higher in 2022 than in 2020, except in September (Table 4). As a consequence, the 2022 growing season was shorter (-8.5 %) than the first one (164 days) and it accumulated more GDD (+4.3 %) than the 2020 growing season (2,317 GDD) (Figure 4).

Evaluating the hydroclimatic balance of the experimental area for the last 31 years (1992-2022) in the May-

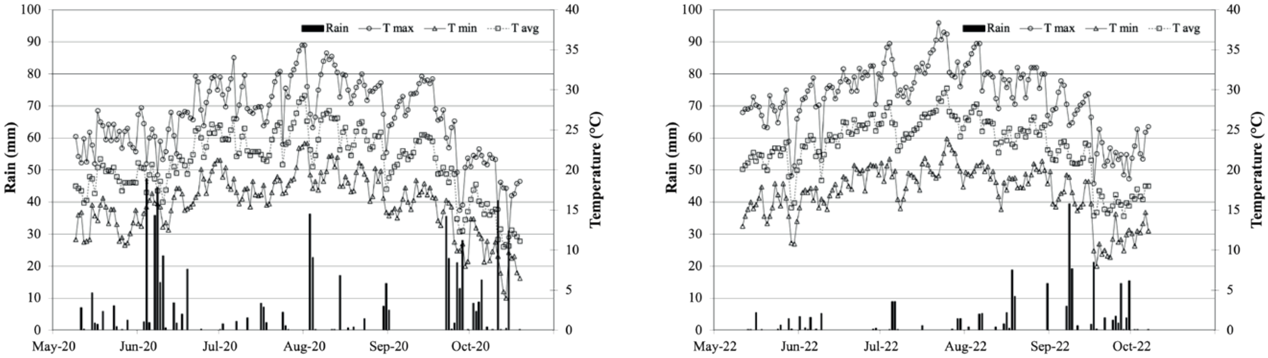

Figure 3. Rainfall and temperature trends recorded during the 2020 and 2022 growing seasons.

Table 4. Monthly average temperatures (°C) in 2020 and 2022 and delta temperature between the years.

Month	Temperature (°C)		D Temperature 2022-2020 (°C)
	2020	2022	
May	18.7	20.9	+2.2
June	21.1	24.2	+3.1
July	23.9	26.3	+2.4
August	24.3	25.1	+0.8
September	20.2	19.0	-1.2
October	13.7	17.1	+3.4

October timeframe (Figure 5), the rain volume exceeded ET0 only in 25.8% of the years, as in 2020. Among the negative values, the water deficit was lower than 350 mm only in 2003, as in 2022. The distribution of the annual water deficit was as follows: between 0 and -100 mm in 25.8% of the years, between -100 and -200 mm in 19.4% of the years, between -200 and -300 mm in 16.1% of the years, and between -300 and -400 mm in 12.9% of the years.

Different rain quantities and distributions between the two seasons were recorded from soybean sowing

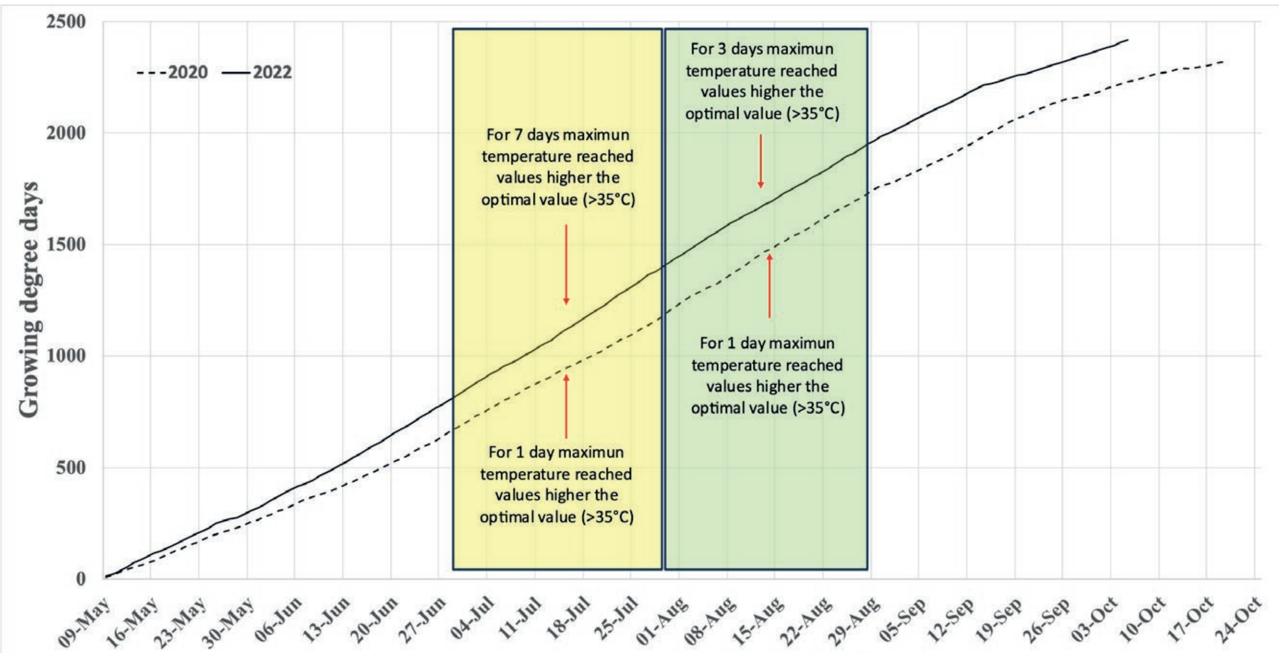

Figure 4. Accumulation of soybean growing degree days over the two growing seasons (dashed line, 2020; solid line, 2022). Yellow and green boxes indicate July and August, respectively.

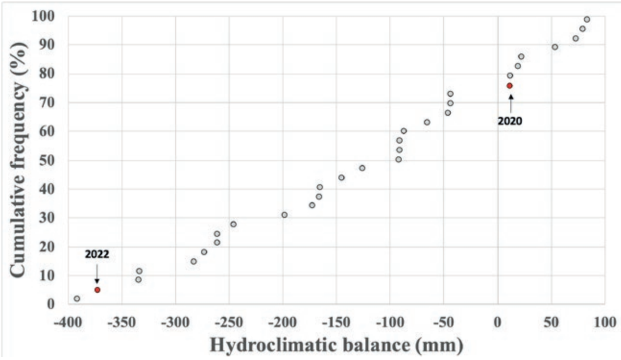

Figure 5. Cumulative frequency of the May-October hydroclimatic balance (mm) over the 1992-2022 period.

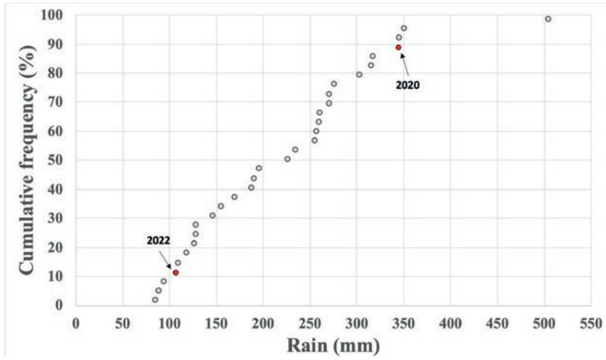

Figure 6. Cumulative frequency of June-August cumulative rainfall (mm) over the 1992-2022 period.

to harvesting (627 mm in 2020; 258 mm in 2022) (Figure 3). Conversely, similar ETmax values were calculated (372.3 mm in 2020; 381.0 mm in 2022) (Table 5). In addition to the low rainfall, the 2022 growing season was characterized by a non-optimal distribution for production purposes since 53.6% of cumulative rainfall (138.4 mm) were recorded in September. Rainy days with rain higher than 10 mm were 125% more frequent in 2020 than in 2022 (8 days).

Focusing on the irrigation season (June-August), 2020 and 2022 were the fourth wettest (344.4 mm) and the fourth driest (107.4 mm) year in the last 31 years, respectively (Figure 6). The opposite cumulative rainfall values in the two years reflect a long-lasting trend (1992-2022) showing cumulative rainfall between 100 and 200 mm in 38.7% of the years and between 250 and 350 mm in another 38.7%. In 2020, June rainfall was the highest (206.6 mm) recorded in the last 31 years, whereas only 15.8 mm were recorded in June 2022 (Table 5). July was a dry month in both years (34.0 mm rainfall in 2020; 27.4 mm in 2022; values usually exceeded with a probability of 77.4%). However, maximum temperatures greatly differed in July, and even in August (Figure 4): they were much higher in 2022 than in 2020, and rainfall was lower (-38.2%) (Table 5). Cumulatively (rain + irrigation), soybean received 678 mm *vs*. 412 mm during the growing seasons of 2020 and 2022, respectively. The irrigation volume represented 7.5% of the cumulative water supplied in 2020 *vs*. 37.4% in 2022.

3.2. Soybean yield and quality

Soybean grain yield was significantly affected by the year, irrigation, and their interaction (Table 6). Irrigation had no significant effect on grain yield in 2020 (mean 4.6 Mg ha^{-1}), while it increased it by 157% in 2022 compared to the rainfed treatment. The mean values across the two years showed a linear correlation between grain

Table 5. Rainfall, maximum crop evapotranspiration (ETmax)* and irrigation volumes in the 2020 and 2022 growing seasons.

Month	2020 growing season						2022 growing season					
	Rainfall (mm) (1)	Number of rainy days	Rainy days (> 10mm)	Irrigation (mm) (2)	ETmax (mm) (3)	Water balance (mm) (1+2-3)	Rainfall (mm) (1)	Number of rainy days	Rainy days (> 10mm)	Irrigation (mm) (2)	ETmax (mm) (3)	Water balance (mm) (1+2-3)
May	41.0	10	1	0	37.8	+2.9	12.0	8	0	0	37.4	-25.4
June	206.6	13	6	0	86.7	+119.9	15.8	8	0	30	89.5	-43.7
July	34.0	10	0	51	134.0	-49.0	27.4	8	0	79	141.5	-35.1
August	103.8	10	3	0	73.2	+30.6	64.2	10	3	34	79.4	+18.8
September	129.0	9	5	0	31.6	+97.4	138.4	15	5	0	28.7	+109.7
October	112.2	11	3	0	9.0	+103.2	0.6	3	0	0	4.4	-3.8
Σ	626.6	63	18	51	372.3	+305.0	258.4	52	8	154	381.0	+20.5

ETmax = Maximum possible water loss through evapotranspiration under ideal conditions without water limitations

Table 6. Soybean grain yield, straw production and water use efficiency (WUE) (average ± SD) under irrigated and rainfed conditions in 2020 and 2022. Different letters indicate significant differences (p<0.05).

Year	Irrigation	Grain (Mg ha-1)	Straw (Mg ha-1)	WUE (kg mm-1)
2020	Rainfed	4.5 ± 0.7 a	3.4 ± 0.7 ab	7.1 ± 1.2 a
	Drip irrigation	4.6 ± 0.5 a	2.9 ± 0.6 bc	6.8 ± 0.8 a
2022	Rainfed	1.0 0.5 c	2.5 ± 1.0 c	4.0 ± 1.9 c
	Drip irrigation	2.7 ± 0.5 b	4.1 1.0 a	6.4 ± 1.1 ab

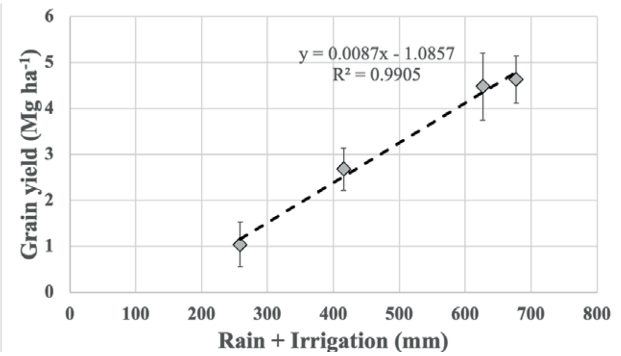

Figure 7. Correlation between water availability and soybean grain yield.

yield and total water availability during the growing cycle (Figure 7). A notable yield increase was observed from 258 to 627 mm of supplied water, with an increase in grain production of 10.7 kg ha^{-1} for each mm. The maximum grain yield was obtained in 2020, with a water volume supply ranging between 627 and 678 mm. CC and the soil amendment type did not have any significant effect on grain yield.

The soybean straw production significantly increased when the soil was amended with digestate solid fraction (+17.3%) compared to compost (2.98 ± 0.69 Mg ha^{-1}), and under irrigation (+20.1%) compared to rainfed (2.94 ± 0.76 Mg ha^{-1}). The 'year x irrigation management' interaction also influenced straw production, with a higher production under rainfed conditions in the rainier year and the opposite in the drier year (Table 6).

Considering the grain quality characteristics, only irrigation significantly influenced the protein content. It induced a reduction from 43.2 ± 1.3% to 42.6 ± 0.9%, while none of the factors under study influenced the oil content (mean 21.9 ± 0.7%).

3.3. Harvest index and water use efficiency

The HI was significantly higher in the wetter year (2020), with no difference between the two treatments (mean 0.59). The HI was lower in 2022 than in 2020, with a significantly higher value under the irrigated treatment (0.41) than under the rainfed one (0.28).

WUE was significantly influenced by the year, irrigation, and their interaction (Table 6). The highest values were obtained in the wetter year, with no significant difference between the irrigated and rainfed treatments (mean 7.0 kg grain mm^{-1}). In the less rainy year (2022), irrigation increased WUE by 60.1% compared to the rainfed treatment (4.0 kg grain mm^{-1}). WUE was not significantly different across the years under the irrigated treatment.

3.4 Irrigation and contribution to economic sustainability

The balance of drip irrigation economic sustainability was negative in both years (Table 7), showing that this irrigation method is not sustainable for soybean within the economic framework of the study area. In 2020, when the rainfall volume satisfied almost the entire crop water requirements (92.5%), the Drevenue due to the limited increase in grain production of the irrigated plots (+ 3.4%) was insufficient to cover the irrigation costs. In 2022, the irrigation provided 37.4% of the total water supplied during the growing season, and brought a grain yield increase of about 157%. Moreover, the grain price of soybean increased by 58.6% due to geopolitical reasons in 2022. However, for that same reason, the cost of annual irrigation equipment (drip tape) simultaneously increased by 111.4%. Both these aspects, together with the unusual meteorological conditions (especially maximum temperatures, Figure 4), caused a low absolute grain yield even under irrigated conditions and resulted in a negative balance in 2022.

An overall assessment of the contribution of drip irrigation to the economic sustainability of soybean production is presented in Table 8. Out of the twelve possible scenarios analyzed in this study, only one shows a clear economic benefit from drip irrigation, i.e., the scenario with low costs, high irrigation effects on yield increase and high market prices. The minimum price that would cover irrigation costs in that scenario is 430.00 € Mg^{-1}. Conversely, the minimum price of soybean that would cover irrigation costs under high effects of irrigation on the yield increase and high irrigation costs is 709.00 € Mg^{-1}. This is an exceptional scenario that occurred under conditions of severe supply difficulties, and therefore an unrealistic one under ordinary conditions to date.

Table 7. Balance of the economic sustainability (€ ha^{-1}) of the drip irrigation system.

Balance items	Growing season	
	2020	2022
*Revenue (€ ha^{-1}) = yield (Mg ha^{-1}) * price (€ Mg^{-1})*		
Irrigated treatment (drip irrigation)	1,780.94	1,634.11
Rainfed treatment	1,722.88	636.45
Δrevenue	58.07	997.66
Irrigation costs (€ ha^{-1})		
Depreciation costs of durable components	235.00	235.00
Direct costs for irrigation equipment purchase	350.00	740.00
Equipment and labor needed to set up and remove the irrigation system	90.00	90.00
Costs of labor during the irrigation season	7.50	50.00
Fuel needed for the engine used to put the drip irrigation system in pressure	10.00	40.00
Σcosts	692.50	1,155.00
Economic sustainability of irrigation (€ ha^{-1}) = DRevenue (€ ha^{-1}) - Irrigation costs (€ ha^{-1})	-634.43	-157.34

NB: Irrigation costs refer to an irrigation system serving 20 ha.

Table 8. Economic scenario analysis.

Grain Price	Irrigation Costs	Low Dyield	High Dyield
Low	Low	-634.43	-64.95
	High	-1,097.25	-527.45
High	Low	-600.93	+302.62
	High	-1,063.43	-157.34

NB: 2020 was characterized by a low price of soybean, low costs and a low Dyield; 2022 was characterized by a high price of soybean, high costs and a high Dyield.

4. DISCUSSION

Irrigation was the sole factor with significant effect on grain yield in relation to the amount and distribution of rainfall among the factors studied in the present work, except for the effect of soil amendments on aboveground biomass production. Irrigation increased grain yield only in the less rainy year (2022), with a recurrence time of 12.9%. This points to the need to plan for possible irrigation in relation to the course of rainfall throughout the year and confirms the results of a study conducted by Ray et al. (2015) aimed at globally estimating the contribution of weather conditions to the yield variability of major extensive field crops: weather conditions have a significant influence on soybean yield in 67% of the regions where it is grown.

Considering the inter-annual yield variation, a yield reduction was observed under both rainfed and irrigated treatments. However, the yield variation between the two years was lower under irrigation management, confirming that irrigation contributes to increase and stabilize yield over time (Grassini et al., 2014). The lower grain yield observed in the second year, even though irrigation was supplied, is attributable to heat stress because temperature exceeded the optimal maximum temperature for ten days in July and August. As recently observed by Jumrani and Bhatia (2019), the seed yield of soybean plants under drought stress at the reproductive stage decreased with the increase of day/night temperatures (30/22 °C -55%, 34/24 °C -59%, 38/24 °C -62% and 42/28 °C -65%) compared to the seed yield of well-watered plants. In our experiment, the irrigated treatment (where full crop water requirement was supplied) showed a yield decrease of 42.1% in 2022 (the year with higher temperature stress conditions) compared to 2020. In the same years, the seed yield decreased by 76.8% under rainfed conditions. Therefore, our data confirm that temperature stress further increases the detrimental effect of drought stress.

A positive correlation between grain yield and water availability during the flowering and grain filling stages has been observed by various authors (Brevedan and Egli, 2003; Chen and Wiatrak, 2010; Sobko et al., 2020). Our results confirm what is reported in these studies. In the less rainy year, rainfall was mainly concentrated in the late part of the crop cycle (August-September), and the soil water content maintained by irrigation between the flowering and grain filling stages increased the yield by 157%. Limited precipitation and a reduced soil water content have also been identified as main limiting factors for soybean seed yields (Gajić et al., 2018). Looking at the water requirements to maximize grain production, our data (from 627 to 678 mm) are within the range reported by Doorenbos and Kassam (1979) who estimated that the water requirement is between 450 mm and 700 mm for maximum production by soybean, depending on climate and the length of the growing period.

A positive effect of irrigation was also observed in terms of WUE, especially in the drier year. WUE values ranging from 0.69 ± 0.03 to 1.16 ± 0.06 kg m^{-3} were obtained by Anda et al. (2020) comparing two soybean genotypes. These authors observed that water stress during the reproductive stage improved WUE irrespective of the season and variety. In our study, WUE values ranged from 0.39 ± 0.18 to 0.86 ± 0.14 kg m^{-3} but with opposite trends, as higher values were obtained under higher rainfall conditions. This can be attributed to the particularly stressful conditions observed in the second year that significantly reduced grain yield despite irrigation.

The grain quality results of the present study disagree with Rotundo and Westgate (2009), who concluded from a meta-analysis that water stress reduces the protein and oil contents of soybean grains. In contrast, the increase in grain protein content under rainfed conditions is in agreement with the results of Candoğan and Yazgan (2016) and Kresović et al. (2017). Considering the grain oil content, our data are in line with the results of Pedersen and Lauer (2003) and Mertz-Henning et al. (2017), who did not observe any significant difference in soybean grain oil content between irrigated and rainfed management when comparing different genotypes under different environmental conditions.

The positive effects of irrigation on grain yield should also be considered in terms of the costs associated with irrigation in order to determine its overall and long-term profitability. Few studies have assessed the economic sustainability of drip irrigation. To the best of our knowledge, no study has been done on soybean, and available studies on other crops have reported contrasting results. The sustainability of irrigation certainly depends on the amount of seasonal rainfall and should be evaluated accordingly (Karges et al., 2022). With this in mind, the use of drip irrigation should be carefully evaluated because it has annual initial fixed costs (purchase and installation of drip lines). However, our data indicate that even in a very dry growing season (recurrence time of 12.9% in a 30 years period), drip irrigation it is not economically sustainable.

5. CONCLUSIONS

Among several experimental factors, the results of the present study show that irrigation is a key agronomic technique to reduce soybean yield variability and vulnerability to drought. However, the investment incurred for drip irrigation at the beginning of the crop cycle is not sustainable because of possible high rainfall volumes during the growing season (resulting in the irrigation system being unused) and/or the high uncertainty of annual costs and possible low grain yield due to other reasons.

Climate change is expected to further affect water availability in terms of quantity and distribution, with an increased number of drought stress events for crops. The simultaneous growth of the world population will result in serious food security uncertainties. In this context of an increased frequency of crop drought stress events, drip irrigation may be a key system to increase and stabilize soybean yield in order to pursue the goal of food security, but cost recovery should be assured. Based on the cost analysis, technological and/or agricultural policy solutions geared toward reducing the direct costs of this irrigation system are highly desirable.

ACKNOWLEDGMENTS

This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript only reflects the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them. Spoke 4, Work Package 4.2, Task 4.2.1 "Farm network setup (Living Labs): a network of farms representative of the different agricultural systems to apply innovative technologies for the sustainable management of crops, animals and forests" and Work Package 4.3, Task 4.3.3 "Risk management strategies and policies in the context of climate change".

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