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ORIGINAL PAPER

Improving yield and irrigation water productivity of green beans under water stress with agricultural solid waste-based material of compacted rice straw as a sustainable organic soil mulch

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Abstract

This research aimed at water saving in irrigation by applying deficit irrigation using two strategies, standard drip and partial root drying (PRD), while applying organic and plastic mulch over two growing seasons of green beans. A field experiment was conducted in 2022 and 2023, using four irrigation treatments supplying 100% of the irrigation requirement (IRg), 75% IRg, 50% IRg, and 50% IRg—PRD, and four soil mulching treatments: uncovered soil (UC), plastic mulch (PM), rice straw mulch (RSM), and compacted rice straw mulch (CRSM). The combined effect of deficit irrigation strategies and soil mulching showed that the maximum irrigation water productivity (IWP) of 5.56 kg m^{-3} was achieved under 50% IRg—PRD & CRSM for both growing seasons, followed by 50% IRg—PRD & RSM and 50% IRg—PRD & PM, with 5.19 and 4.96 kg m^{-3}, respectively. The highest yield of 8936 kg ha^{-1} was achieved with 50% IRg—PRD & CRSM, followed by 8914 kg ha^{-1} and 8898 kg ha^{-1} with 100% IRg & CRSM and 75% IRg & CRSM, respectively. The lowest yield of 6009 kg ha^{-1} was obtained with 50% IRg & UC. The highest soil moisture content was observed under 100% IRg & CRSM. The application of organic mulches was found to be particularly effective in conserving soil moisture due to enhanced infiltration, improved retention capacity, and suppression of weed growth, ultimately fostering optimal crop development and higher yield. The results of soil temperature variations beneath soil mulches showed that CRSM is effective in alleviating plant water stress, lowering the temperature below the cover and reducing water loss through evaporation from the soil surface. The combination of 50% IRg—PRD & CRSM produced plants with enhanced plant height, fresh and dry weight, leaf area, pod length, and green bean weight, as well as the highest vegetative growth indices. Generally, the organic mulching increased soil temperature, soil moisture, IWP, and green bean production.

Introduction

Water scarcity poses the greatest obstacle to crop production. Climate change contributes to water scarcity and drought (Tesfaye and Nayak 2022). Water scarcity is currently one of the most pressing global issues, and it will become increasingly essential in the future. More than 40% of global food production comes from irrigated fields, and agriculture is the largest consumer of water, accounting for 70% of all freshwater withdrawals. As water shortage worsens worldwide, improving the efficacy of agricultural water resources becomes a top goal for increased food production (Bosco et al. 2022).

Agricultural industries are under great pressure to rationalize and reduce the use of freshwater intended for irrigation to use it for other farming purposes (Abdelraouf et al. 2020). Water scarcity is a severe issue that challenges food

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production in arid regions. Reducing water consumption and conserving irrigation water is critical to modernizing and creating sustainable and innovative technologies (El–Metwally et al. 2022). Rising agricultural production per unit of irrigation water is a crucial and required goal for rising food demand and requirement at the same rate as the tumultuous surge in population growth (Abdelraouf and Ragab 2018; Eid and Negm 2018).

Partial root-zone drying (PRD), a cutting-edge method of trace irrigation, splits the crop's root zone into two halves. This technique basically involves watering half of the root zone of the plant or tree and letting the other half dry. The previously irrigated half of the root zone is then left to dry, and the dry half is watered after a predetermined period of time (Iqbal et al. 2020).

Mulch is a substance, either organic or inorganic, that is applied to the soil's surface to protect it from precipitation, sunlight, and evaporation. Mulches aid in maintaining moisture, controlling weed growth, enhancing soil stability, and preventing physical attacks by insects and pests. According to Kaur et al. (2021) organic mulches contribute nutrients and humus to the soil, suppress weeds effectively, slow down the rate of evaporation, and aid to stabilize soil temperature. Almost all of the benefits of soil mulching are due to the ability to manage the microclimate around the plants. Soil mulch governs microclimate based on its thermal qualities, such as reflectance and the absorption or transmittance of incoming solar radiation (Moursy 2021).

Alhashimi et al. (2023) found that organic mulch is more advantageous than black plastic cover. Soil mulching with organic mulches is one of the natural solutions in this regard. It is possible to achieve this by employing plant mulches and straw mulches left over following cereal grain harvest (Liebman and Davis 2009; Kosterna 2014; Rhioui et al. 2023). Furthermore, straw mulch increased soil temperature during the colder seasons and decreased it during the warmer seasons when compared to bare soil (Moursy et al. 2015). A good way to conserve soil moisture and promote sustainable crop production is to choose and apply the right mulch, which can reduce transpiration and evaporation by suppressing weeds and covering increased water intrusion while reducing water loss. More research is needed to fully understand the effects of mulch on cultivated land in the short and long term (Steinmetz and Schröder 2022).

At present, irrigated agriculture faces the issue of increasing crop yields while utilizing less water. One possible approach is to use a combination of mulching, drip system, and deficit irrigation (Igbadun et al. 2012). The combination of two affordable methods, PRD and mulch, can be a more effective strategy to reduce water consumption, while also improving resistance to drought stress. Mulch is an application of material with multiple benefits for both soil and plants, such as enhancing soil penetration, decreasing water runoff, reducing evaporation losses, and impeding the growth of weeds (Alhashimi et al. 2023).

Over the past years, organic soil mulch has gained more attention as an environmentally friendly application. It increases the soil's organic matter content, which increases the soil's capacity to conserve water as well as reducing the use of mineral fertilizers. According to the Web of Science Index the number of published studies utilizing plastic mulch has started to decline, while the number of published studies utilizing organic soil mulches has increased (Fig. 1A, B). Using terms like “organic soil mulch”, “agricultural”, and “water management” as keywords it was found that 701 research papers were published between 2000 and 2024, with 86 publications in 2022, 86 in 2023, and 16 in 2024; while there were 687 articles between 2000 and 2024 for the keywords "agriculture", "water management," and "plastic soil mulch"; 110 of those studies were published in 2022, 89 in 2023, and 6 in 2024. These publications show the tendency toward the use of green or organic materials in agriculture. This classification illustrates how plastic and organic soil mulch interact and what effects they have on yield, weed control, soil health, soil organic matter, and water use efficiency. Figure 2, which depicts the ranking of nations based on published papers about organic mulch, shows that, from 2000 to 2024, the United States ranked first with 146 articles, while Egypt ranked at number 20 with only 4 articles.

This research was carried out to address a gap in the existing literature in arid and semi-arid regions. Plastic soil mulches are deemed environmentally hazardous but, while organic mulches are environmentally friendly, they are less effective than plastic because of their higher permeability, allowing air to pass through easily, resulting in increased evaporation rates during the day and exposing plants to frost during the night. Subsequently, the concept of compressing rice straw emerged as a solution, as it is a significant untapped resource of agricultural waste in Egypt. The compression aims to reduce the interstitial pores in the soil, thereby restricting air movement and providing similar benefits to plastic mulches.

The main objectives of this research are to i) investigate the suitability of partial root drying (PRD) and mulching techniques when growing green beans in sandy soil, ii) studying the impact of PRD + organic mulch on green beans characteristics, yield and water productivity under arid conditions, and iii) studying the relationship between the temperature on the soil surface and that of the root zone under compacted organic mulch and their effects on biological activity of microorganisms within the root zone and on soil physical, chemical and biological properties.

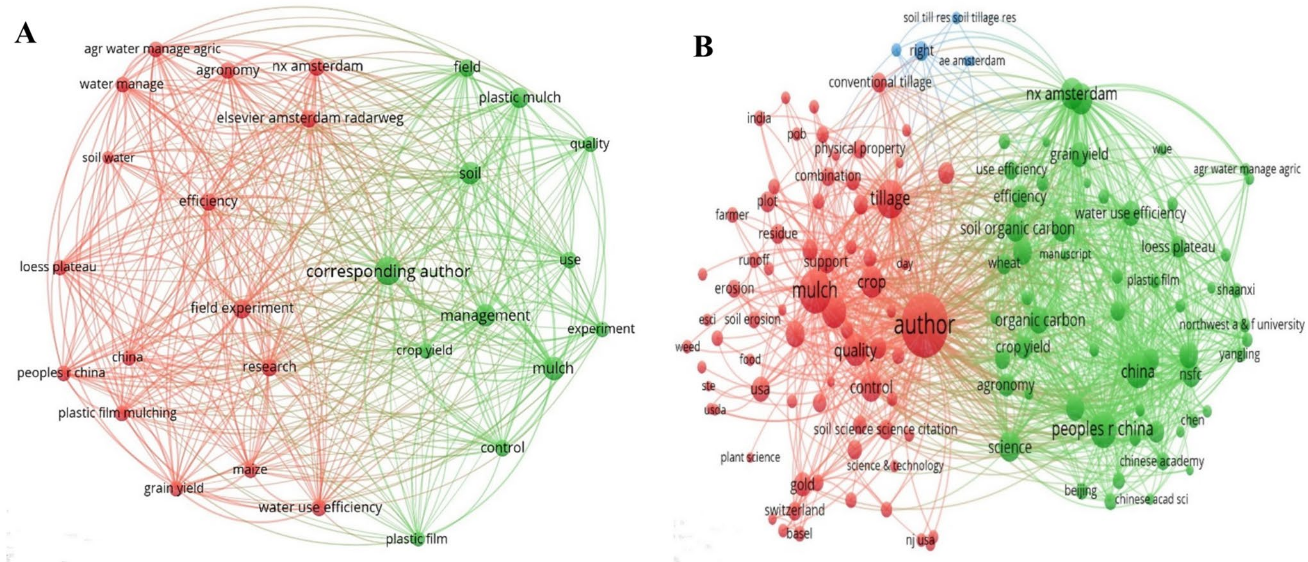


Fig. 1 A systematic review analysis of matching documents using selected keywords for 1995–2023 all over the world related to **A** plastic soil mulch (687 documents) and **B** organic soil mulch (701 documents)

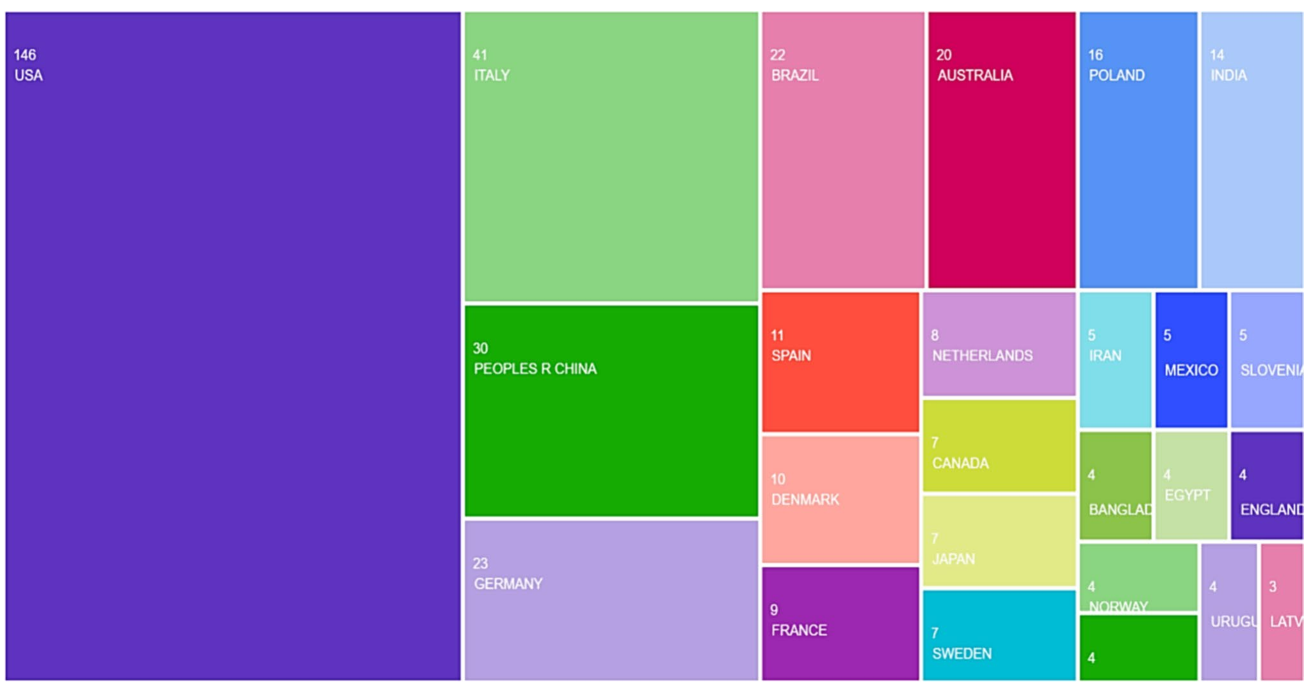


Fig. 2 Ranking of countries from highest to lowest in the number of published research on organic mulches from 2000 to 2024

Materials and methods

Experimental location

The study was carried out at the National Research Center farm in EL-Nubaria, EL-Beheira Governorate, Egypt, during the 2022 and 2023 growing seasons. The study area is situated between 30° 29′ 48.9" N—30° 29′ 46.1" N and 30°18′ 49.6" E—30° 18′ 56.0" E, with an average elevation of 21 m above sea level (Fig. 3).

With 85.4% sand, 9.5% silt, and 5.1% clay, the soil has a sandy composition. Its pH is 7.7, its salinity was determined using electric conductivity (EC), which came out to

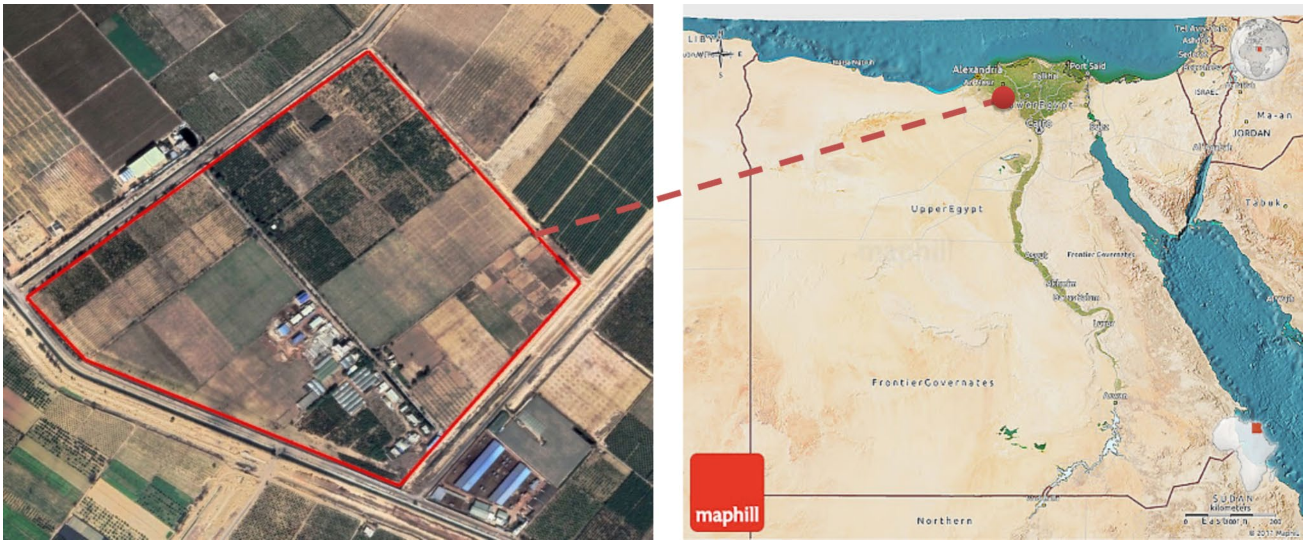


Fig. 3 The study area

Table 1 Chemical characteristics of the irrigation water

SAR	Anion (meq L^{-1})				Cation (meq L^{-1})				EC (dS m^{-1})	pH
	SO_4^-	Cl^-	HCO_3^-	CO_3^-	K^+	Na^+	Mg^{++}	Ca^{++}		
2.68	1.43	1.74	1.14	0.74	0.33	2.61	0.64	1.47	0.43	7.18

be 1.67 dS m^{-1}, and the top 30 cm contain 0.41% organic matter. Available soil N, P, and K values were 17.2, 4.3, and 25 mg kg^{-1} soil, respectively, and extractable Fe, Mn, and Zn levels were 2.99, 1.75, and 0.67 mg kg^{-1} soil. The chemical characteristics of irrigation water are shown in Table 1. The irrigation water was drawn from an open channel in the experimental region and had an average electrical conductivity of 0.43 dS m^{-1} and pH of 7.18 (Table 1).

Climatic conditions

The setting of the experiment, which took place in an open field, was characterized as having an arid climate with chilly winters and steamy summers. The following variables related to the climatic conditions were recorded every day during each growing season: an on-site weather station provided the maximum and minimum air temperatures as well as the average and relative air humidity and number of sunshine hours during the season (November to January). The total amount of precipitation per year was extremely little (20 mm) *(*Table 2*).*

Table 2 Monthly environmental condition variables in the greenhouse for the two cultivated seasons

Year	Climate parameter	Month		
		February	March	April
2022	T_{min}	9.12	10.87	13.92
	T_{max}	23.00	25.31	32.21
	T_{ave}	16.06	18.09	23.07
	RH (%)	53.84	46.00	38.54
	WS (m sec^{-1})	3.82	4.21	4.17
	Solar radiation (MJ m^{-2})	11.35	19.26	24.34
2023	T_{min}	6.70	10.15	12.06
	T_{max}	20.00	24.00	28.41
	T_{ave}	13.35	17.08	20.24
	RH (%)	60.58	51.57	43.59
	WS (m sec^{-1})	3.50	4.22	4.35
	Solar radiation (MJ m^{-2})	15.21	19.77	23.67

Crop evapotranspiration and irrigation scheduling

The crop evapotranspiration calculation was based on the Food and Agriculture Organization of the United Nations, FAO. The the reference evapotranspiration (ETo) is based on the Modified Penman–Monteith equation, FAO 56 (Allen et al. 1998) was calculated by applying daily meteorological parameters measured within the experimental site. The ETo was calculated according to the FAO calculator (http://www.fao.org/land-water/databases-and-software/eto-calculator/en/). The CLIMWAT 2.0 and CROPWAT 8.0 programs were applied based on Eq. 1 to estimate the green bean evapotranspiration.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

where ETo represents the reference evapotranspiration (mm day^{-1}), Rn represents net radiation at the crop surface (MJ m^{-2} day^{-1}), G represents soil heat flux density (MJ m^{-2} day^{-1}), T represents the mean daily air temperature at 2 m height (°C), U_2 represents wind speed at 2 m height (ms^{-1}), and es Andean represents saturated vapor pressure deficit (kPa). The crop's evapotranspiration remains calculated using the methodology and processes outlined in the FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998) and it already represents the daily plant water consumption through the collection of water evaporation from soil and water transpiration from plant leaf stomata and evaporation:

$$\mathrm{ET_C} = ET_O \times Kc \tag{2}$$

where K_c represents the crop coefficient, and ETo represents the daily reference evapotranspiration (mm day^{-1}). The gross irrigation requirements for green beans was performed by the following equation of Brouwer and Heibloem (1986):

$$\mathrm{IR}_g = \left(\frac{\mathrm{ET}_O \times K_c \times K_r}{E_i}\right) \tag{3}$$

where IR_g is the gross irrigation requirement (mm day^{-1}), E_i is the irrigation efficiency (%), ETo is the reference evapotranspiration, Kc is the crop coefficient, and K_r represents the ground cover reduction factor; the values of Kr are calculated by Keller equation (Eq. 4) as follows:

$$K_r = GC + 0.15(1 - GC) \tag{4}$$

where GC, the ground cover (%), is determined through dividing the shaded area per plant over the whole plant area.

Crop administration

Three green bean (*Phaseolus vulgaris L.*) seeds were planted adjacent to each emitter on the 1st of February in both 2022 and 2023. The application of fertilizers was executed in the following manner: nitrogen (50 kg ha^{-1}), phosphate (20 kg ha^{-1}), and potassium (41.5 kg ha^{-1}) were administered utilizing ammonium sulphate (20.5%), calcium superphosphate (15.5%), and potassium sulphate (48%). The fertilization regimen involved six equal weekly doses of nitrogen, with the initial dose occurring two weeks post-planting; phosphate was applied in full prior to planting, while potassium was introduced in two equal biweekly doses commencing five weeks after planting. Manual harvesting was conducted around 75 days subsequent to planting.

System installation and experimental treatments

A field plot measuring 8.4 by 24 m was chosen for the experimental investigations. This specific field plot was segmented into 16 identical plots of 2.1 by 6 m. Each of these plots consisted of three rows spaced 0.7 m apart and represented a unique treatment with three replications. The experimental design employed for both growing periods was a split-plot design. The main plot was assigned the deficit irrigation treatments (100% IRg, 75% IRg, 50% IRg, and 50% IRg PRD). Within the subplot, the soil mulch treatments (uncovered soil (UC, Control), plastic mulch (PM), rice straw mulch (RSM), and compacted rice straw mulch (CRSM)) were distributed, and each treatment was replicated thrice (R1, R2, and R3) (Fig. 4).

The initiation of the trickle irrigation system setup took place in January 2022 within a controlled environment, incorporating a media filter, screen filter, backflush mechanisms, and a fertilizer injection system utilizing the Venturi effect. The positioning of the trickle tape (Euro drip GR) was meticulously executed in straight lines along the ridges, with the tape strips featuring openings on their upper surfaces. Drippers in the installed trickle system were spaced 30 cm apart, each providing an application rate of 4.0 L h^{-1}. To regulate water application and quantify the discharge, each plot was equipped with a gate valve and flow meter.

Production of compacted rice straw mulch

Three polymers were applied as follows; CMC (Carboxymethyl cellulose (CMC) is a derivative of cellulose, containing carboxymethyl groups that are generated via the reaction of cellulose with chloroacetate in alkali to produce substitutions in the C2, C3, or C6 positions of glucose units (Gelman 1982). As a result, CMC is water soluble and more amenable to the hydrolytic activity of cellulases. CMC is therefore a useful additive to both liquid and solid medium for the detection of cellulase activity, and its hydrolysis can be subsequently determined by the use of the dye Congo red, which binds to intact β-d-glucans. Zones of clearing around colonies growing on solid medium containing CMC, subsequently stained with Congo red, provides a useful assay for detecting hydrolysis of CMC and therefore, β-D-glucanase activity (Teather and Wood 1982). The inoculation of isolates onto membrane filters placed on the surface of CMC agar plates is a useful modification of this technique, as the filter may subsequently be removed allowing visualization of clear zones in the agar underneath cellulolytic colonies.

Hydroxyethyl cellulose (HEC) polymer is a representative green and renewable water-soluble cellulose derivative with a large number of active hydroxyl groups inside, providing enough cross-linking sites for CA and facilitating the graft of β-CD in hydrogel films (Chu et al. 2020;

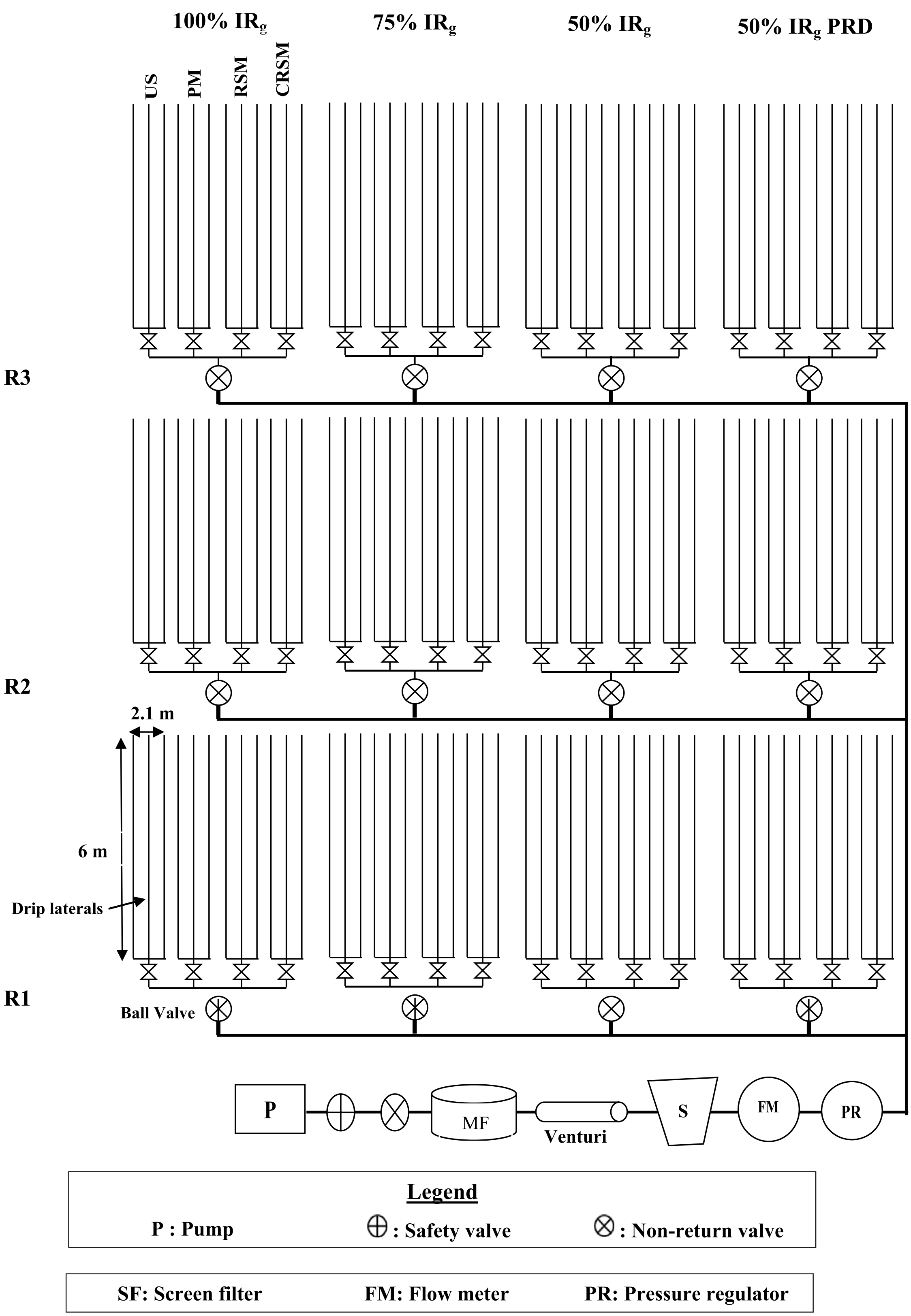


Fig. 4 A hydraulic diagram of the micro irrigation system and treatments

Shi et al. 2020). The preparation of (Sampatrao Ghorpade et al. 2018) the β-CD-HEC hydrogel films. And it also lists several crosslink types of the structure. From the exploration of the mechanism, it is mainly prepared by esterification crosslinking. In addition, its large swelling rate and degree of cross-linking make it beneficial to drug delivery applications.

Polyacrylamides (PAMs) are relatively inexpensive polymers that are easily formulated to high molecular weights about several million g/mol. PAM was first used in the paper industry in the mid-1950s. Anionic PAM usually contains about 5% polyacrylic acid groups formed by copolymerization of acrylamide and acrylic acid monomers or by hydrolysis of PAM photopolymer under conditions to convert some of the amide groups to carboxylate salts. PAM with as much as 50% acrylic acid is used. Cationic PAM is made by copolymerization of acrylamide monomers with cationic monomers (Bajpai 2018).

The cutting of the rice straw into small pieces was followed by its incorporation into a large metal bowl together with adding CMC or HEC polymers were prepared through hot flipping to 70 °C for 3 h, with concentrations of 15% (150 g L^{-1}). PAM polymer was prepared by melting with Cold-pressed for 3 h, while the best result was obtained using 5% (5 g L^{-1}) of PAM polymer and it was added after complete dissolution of the polymer in water on rice straw and subsequently, the mixture was promptly transferred to a level container measuring 30 cm by 40 cm and subjected to compression using a force equivalent to 100 kg m^{-2}. An area of one square meter necessitates half a kilogram of rice straw coverage, indicating that 5 tons of rice straw are essential for a hectare (Fig. 5).

Fig. 5 The production of compacted organic mulching

An application rate of 18 ton ha^{-1} was utilized for rice straw mulch, whereas compacted rice straw mulch was applied at a rate of 5 ton ha^{-1}. The chemical composition of the rice straw employed in the field trials can be found in Table 3.

Measurements

Soil moisture content and temperature of root zone

Soil moisture levels were assessed within drip irrigation systems in accordance with Levin et al. (1979). The soil moisture readings were collected at intervals of 0–10, 10–20, and 20–30 cm along the X-axis (surface layer) and 0–10, 10–20, and 20–30 cm along the Y-axis (depth of soil). The quantification of moisture content in the soil was conducted using a soil moisture probe, which underwent calibration through the gravimetric technique. A Time Domain Reflectometry (TDR) device, specifically a three-pin borehole probe with an adapter from Eijkelkamp Agri-research Equipment in the Netherlands, featured a polycarbonate rod with a 25 mm diameter. This device incorporated electronic sensors arranged in stainless steel rings at equal intervals along the length of the rod. The soil moisture content was analyzed 5 cm away from the emitter utilizing TDR. The soil moisture levels were maintained between field capacity and the refill point, corresponding to 50% of the total water available in the soil. To evaluate the impact of soil mulching on water retention, soil organic matter, and soil moisture content, measurements were taken both before and 2 h after irrigation.

To investigate the influence of various mulches on soil temperature in real-world settings, weekly assessments of maximum and minimum temperatures at the soil surface and 10 cm depth were carried out in each plot. This was achieved using a digital thermo-hygrometer (YIERYI, Shen Zhen Yage Technology Co., Ltd, a versatile 4-in-1 tool for digital soil pH measurement, moisture analysis, temperature recording, and sunlight monitoring).

Table 3 The chemical composition of rice straw

Component	
Moisture (%)	19.00
Cellulose (%)	32.00
Nitrogen-free extract (%)	4.40
Potassium (%)	0.21
Lignin (%)	13.30
Calcium (%)	0.16
Phosphor (%)	0.11
Magnesium (%)	0.12
Sulfur (%)	0.07
Cobalt (mg kg^{-1})	0.06
Copper (mg kg^{-1})	0.51
Manganese (mg kg^{-1})	0.42
Ash (%)	18.13
Silica (%)	12.50

Microorganism's activity within the root zone

Soil samples were procured from the rhizosphere of the cultivated crop across all treatment groups in three replicates prior to the harvest period, in order to quantify the total population of microorganisms present in the root-zone. Colony-forming unit (CFU) is a unit which estimates the number of microbial cells (bacteria, fungi, viruses etc.) in a sample that are viable, able to multiply via binary fission under the controlled conditions in CFU mL^{-1}. These are an indication of the number of cells that remain viable enough to proliferate and form small colonies. The enumeration of microorganisms (CFU) within each treatment was conducted at the culmination of both growing seasons of green beans.

Vegetative growth status of green beans

The period of flowering initiation was established by enumerating the days from seed sowing to the point at which 50% of the plants within a plot exhibit flower production, as ascertained through visual assessment. Days to maturity were defined as the duration from sowing to the point at which 50% of the plants within the plot are deemed ready for harvesting, as determined through visual inspection. Mature pods are characterized by their firm and fleshy nature, containing small green immature seeds.

The mean value of various vegetative characteristics of green bean plants was assessed at four distinct intervals starting from the planting date (at 20, 30, 40, and 50 days post-planting) to ascertain fresh weight (g), plant stature (cm), leaf surface area (cm^2), and overall chlorophyll content (mg L^{-1}). Utilizing the Minolta Chlorophyll Meter, SPAD-502, and Spectrum Technologies10, the total chlorophyll concentration was gauged. Specified plants, chosen at random from each watering regimen, were individually isolated to determine their dried plant weight (g), with the mean shoot dry weight (g) of each plant being computed subsequent to desiccating all four sets of vegetation from each section for a day in an oven set at 65 °C. The collective leaf area (cm^2) of the entire plant from four plants in each section was quantified utilizing a leaf area gauge (Model CI 202, Germany), and then estimated per plant. The length of pods was gauged from the junction where the pod appeared to the tip of the pod, averaging data from four designated plants in each section.

Determination of pod nutrient and nitrate conten

The Kjeldahl method (Velp, UDK 129) was applied to the extract in order to determine N (Makarynska 2022). The Kjeldahl method of determining leaf nitrogen followed a similar process. Pod potassium (K) concentration (%) was determined following the ashing of 0.5 g of dry leaf powder in a muffle furnace for 6 h at 550 °C. After that, the samples were heated to dryness and twice extracted using 2 mL of 1/3 HNO_3 (v/v). After dissolving the ash once more in 2 mL of 1/3 HCl (v/v), hot deionized water was added to dilute the mixture to 10 mL. Using pure water as a blank, the quantity of potassium in the samples was determined using a flame photometer. To create the standard curve, HCl was used to make potassium standard solutions at concentrations of 2.5, 5, and 10 ppm K, which were identical to those in the extract samples. Using dilution factors and a standard curve, the K concentration of the samples was determined (Saghaiesh and Souri 2018). The phosphorvanadomolybdate technique was used to measure the P. The dry matter percentage (dried at 105 °C) was used to express the results.

Quality parameters

The Bradford method (Bradford 1976) was used to calculate the percentage of protein in pods. After the pods were ground and dried at 50 °C for 48 h, 0.3 g of the dry powder was employed in a wet digestion process with oxygen peroxide and salicylic acid to determine the protein content. Following that, 2.5 mL of sulfuric acid were added to each sample, and they were incubated for an hour at 280 °C. The measurements were multiplied by 6.25 to determine the percentage of protein. The percentage of fiber in pods was calculated using (Rai and Mudgal 1988).

Green beans productivity

When the beans reached harvest stage, the fully developed pods were taken out of the middle of each plot's three rows. The mass of all the green beans was calculated for each irrigation strategy. Starting 50 days after planting and ending 75 days later, the 25-day green bean harvest season was in effect. Following harvest, the overall productivity of green beans was calculated in kilograms per hectare (kg ha^{-1}) using a random sample of each plot's economic output of pods for 1 m^2. The entire harvested pod crop was sorted by visual inspection; pods free of disease and insect damage, homogeneous in color, and with a small curvature were deemed marketable. The marketable yield per plot was then translated to kilograms per hectare.

Irrigation water productivity (IWP)

The following formulas from Howell et al. (2015) were used to compute the values of irrigation water productivity (IWP):

$$IWP = \frac{Y}{I} \tag{5}$$

where IWP are the irrigation water productivity (kg m^{-3}), Y is the economic yield (kg ha^{-1}), and I is the irrigation water applied (m^3 ha^{-1}).

The irrigation water application efficiency

Application efficiency relates to the actual storage of water in the root zone to meet the crop water needs in relation to the water applied to the field. According to Abdrabou et al. (2022), application efficiency "AE_{IW}" can be calculated using the following equation:

$$AE_{IW} = \frac{D_S}{D_a} \tag{6}$$

where AE_{IW} is the application efficiency of irrigation water (%), Ds is the depth of stored water in root zone (cm) will be calculated by Eq. (7), and D_a is the depth of applied water (cm).

$$D_S = (\theta_1 - \theta_2) \times d \times \rho \tag{7}$$

where θ_1 is the soil moisture content after irrigation (%), θ_2 is the soil moisture content before irrigation (%), d is the soil layer depth (cm), and ρ represents the relative bulk density of soil (dimensionless).

Statistical analysis

This study's measurements were all subjected to an analysis of variance (ANOVA) suitable for a split-plot design with a randomized complete block design structure, where the main plot was deficit irrigation, the subplots were soil mulching materials, and the blocks were replicates. To assess the interaction between the two components, the error term was the mean square of the product between the deficit irrigation and soil mulching materials. To identify statistically significant differences between average groups in the ANOVA, the least significant difference (LSD) of Duncan's test was employed. Probabilities were significant at less than 0.05. The MSTAT program, which runs on DOS-compatible computers and is written in the C programming language, was used for all analyses (Freed and Peacor 1989). Pearson's analysis and Heatmap correlation were analyzed using an online statistical analysis and visualization program (Mahmoud et al. 2023).

Feasibility study

Economic evaluation will be applied through the calculation of net income by Eq. (8) according to (Anyaegbu et al. 2020).

$$NFI = TR - TC \tag{8}$$

where NFI is the Net Farm Income (US\$ ha^{-1}), TR is the total revenue (US\$ ha^{-1}), TC is the total costs and equal to (total fixed costs (TFC) + total variable costs (TVC)) in (US\$ ha^{-1}). The total fixed costs (US\$ ha^{-1}) including irrigation systems costs, administrative expenses, annual consumption 10% (without land rent), and rent (on season), while the variable costs including the costs of irrigation, seedlings, fertilizers, rice straw mulch, weed control, pest control, and harvesting, total variable costs (US\$ ha^{-1}) equal to total operational costs + energy costs + maintenance. The maintenance costs, taken as 2.2–7.4% of fixed costs (US\$ ha^{-1}), years of working life expectancy (10 years) except for irrigation system main line and sub-main lines.

Results

Yield and irrigation water productivity

Between the two growth seasons, there was little variation in the irrigation water application (IWA). Under 100% IRg, the highest IWA ever measured was 3100 m^3 ha^{-1} in 2022; in 2023, it was 3090 m^3 ha^{-1}. On the other hand, under 50% IRg and 50% IRg PRD, the lowest IWA recorded was 1550 m^3 ha^{-1} in 2022; this dropped to 1545 m^3 ha^{-1} in 2023 (Fig. 6A).

During the second growing season, 50% IRg PRD & CRSM produced the maximum yield, 8936 kg ha^{-1}. Following this were yields of 8914 kg ha^{-1} and 8898 kg ha^{-1}, respectively, with treatments consisting of 100% IRg & CRSM and 75% IRg & CRSM. In contrast, the yield with 50% IRg PRD & UC was the lowest, at 6105 kg ha^{-1}. The 50% IRg PRD & CRSM treatment in 2022 had the highest yield of 8611 kg ha^{-1}. Treatments with 100% IRg & CRSM and 75% IRg & CRSM produced 8599 kg ha^{-1} and 8596 kg ha^{-1}, respectively. Conversely, the 50% IRg & UC treatment had the lowest yield, 6009 kg ha^{-1} (Fig. 6B).

For both growth seasons, the 50% IRg PRD & RSM and 50% IRg PRD & PM treatments produced IWPs of 5.19 and 4.96 kg m^{-3}, respectively, whereas the 100% IRg & UC treatment produced the lowest IWP of 2.45 kg m^{-3} (Fig. 6C). The maximum IWP of 5.56 kg m^{-3} was attained under this kg ha^{-1} and 8596 kg ha^{-1}, respectively. Conversely, the 50% IRg & UC treatment had the lowest yield, 6009 kg ha^{-1} (Fig. 6B).

The interaction effect of deficit irrigation strategies and soil mulches on the irrigation water application efficiency showed that the maximum irrigation water application efficiency 97% under the 75% IRg & CRSM treatment in first growing season followed by the 50% IRg & RSM and 75% IRg & CRSM treatments with 96% and 93% respectively. On the other hand, the minimum irrigation water application efficiency 86% was obtained under the 100% IRg & UC treatment in the second season, while the maximum irrigation water application efficiency 98% was obtained under the 50% IRg PRD & CRSM treatment in 2023 followed by the 50% IRg & RSM and 75% IRg & CRSM treatments, with 97% and 95%, respectively, while the minimum irrigation water application efficiency 87% was obtained under the 100% IRg & UC treatment (Fig. 6D).

For both growth seasons, the 50% IRg PRD & RSM and 50% IRg PRD & PM treatments produced IWPs of 5.19 and 4.96 kg m^{-3}, respectively, whereas the 100% IRg & UC treatment produced the lowest IWP of 2.45 kg m^{-3} (Fig. 6C).

The maximum IWP of 5.56 kg m^{-3} was attained under these treatments. There were substantial differences in yield and IWP across all treatments. The order of the green bean yield and IWP was CRSM > RSM > PM > UC, but the order of the IWP in relation to water stress was 50% IRg PRD > 50% IRg > 75% IRg > 100% IRg. Conversely, 50% IRg PRD > 100% IRg > 75% IRg > 50% IRg was the trend associated with water stress for yield.

Effect deficit irrigation strategies and soil mulches on the relation between soil moisture, soil temperature and air temperature

Figure 7 demonstrates that, as expected and recognized, the moisture content after irrigation was higher than the moisture content before irrigation; however, under the same IWA, the UC treatment's moisture content prior to irrigation was significantly lower than that of the other treatments, and the order of the difference between the moisture content before and after irrigation was UC > PM > RSM > CRSM, while the trend was associated with IWA 100% IRg > 75% IRg > 50% IRg PRD > 50% IRg. Figure 7 shows that the soil moisture content in the green bean plots that were treated to mulching treatments varied in response to watering events. A comparative analysis showed that the average daily soil moisture level in the bare soil (UC) treatment was significantly lower than in the mulching treatment plots, with UC < PM < RSM < CRSM being the order of significance (Fig. 7A).

It is noted that the moisture content of the different treatments before irrigation for the 100% IRg treatment ranged from 6 to 11% before irrigation, and after irrigation the

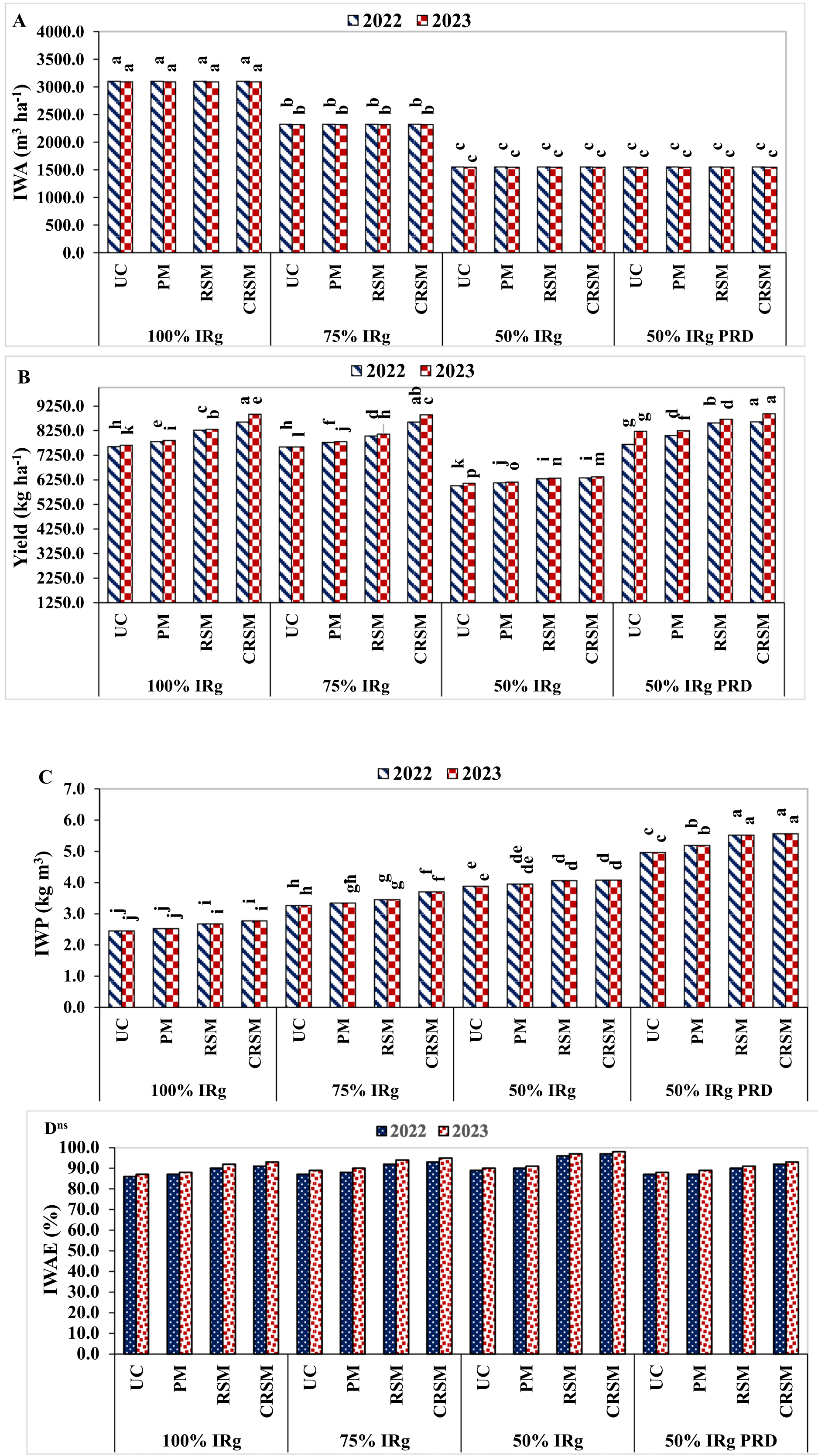


Fig. 6 The effect of deficit irrigation strategies and soil mulch on **A** irrigation water applied (IWA), **B** yield, and **C** irrigation water productivity (IWP) for both growing seasons. Means followed by the different letters within each column significantly differ according to the Duncan multiple comparison test at the 5% level. Each value is the average of three replicates over two seasonsns: non-significant.

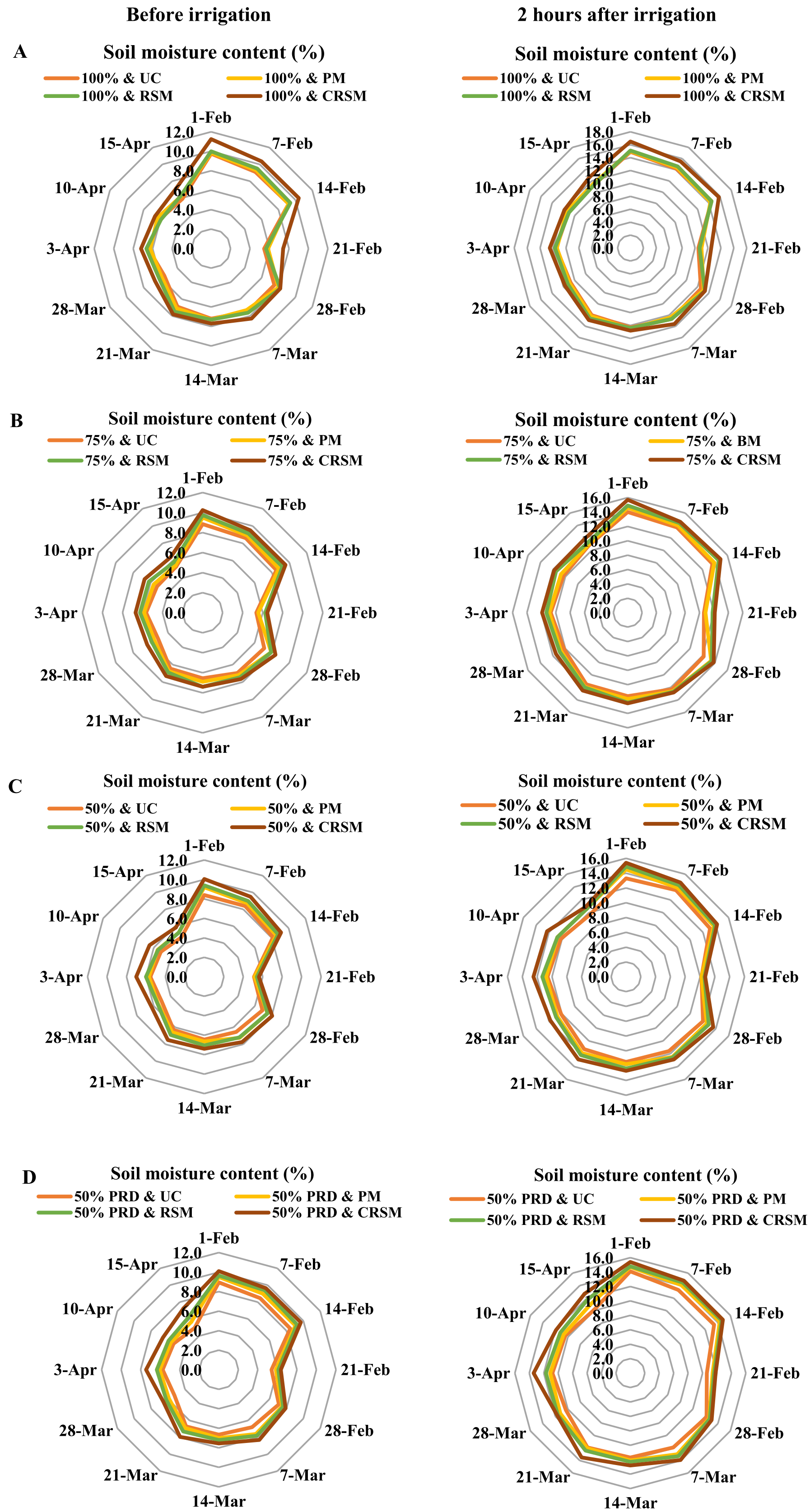


Fig. 7 Effect deficit irrigation strategies and soil mulches on soil moisture content before and after irrigation for different measures as an average of both growing seasons

moisture content increased to reach 12–17%, meaning it exceeded the value of the field capacity of 15%, which is largely the cost, with some losses in quantities of water in excess of the field capacity. In the same context, the moisture content of the soil for the treatment was 75% IRg. Before irrigation, it ranged from 4 to 10%, while after irrigation it reached 10–16%, although there was a decrease in the amount of irrigation water by 25%, which is the same. The trend taken by both treatments, 50% IRg and 50% IRg PRD, before and after irrigation, which gives evidence of the effectiveness of plastic and organic soil covers in reducing evaporation from the soil surface and thus maintaining ground moisture at high levels, even if the effectiveness of CRSM is greater than the effectiveness of RSM (Fig. 7C, D).

Both plastic and organic mulches had an impact on changes in soil temperature (Fig. 8). In both growing seasons, the plastic-mulched soil was warmer than the organic and unmulched treatments. In comparison to the UC treatment, the PM treatment had the greatest mean soil temperature, increasing it by 4–5 °C under various irrigation conditions and at a soil depth of 10 cm. We used the average soil temperature from both growth seasons over the 2 years of the experiment since there was no discernible variation in the mean soil temperature between the 2 years. When compared to UC, the average soil temperature in RSM and CRSM reduced by 9–12 °C at a soil depth of 10 cm, respectively, due to the treatment that had the lowest mean soil temperature: organic mulches. Additionally, the organic soil showed the least variations in temperature before and after irrigation in both years. For UC, PM, RSM, and CRSM, the average difference in soil temperature before and after irrigation was 10.63 °C, 12.73 °C, 8.55 °C, and 6.64 °C, respectively (Fig. 8).

Whether the rice straw covers were compressed or not, the temperatures beneath them were closest to the ambient temperature. This suggests that the covers were effective in moistening the soil and lowering the crop's water stress in the root zone, which in turn lowers the amount of water lost through evaporation from the soil surface. Following irrigation, the temperatures were much colder than they were before, with a 10–15 °C difference in temperature between the two. However, it will have a detrimental effect on weed growth. The highest temperatures, however, were recorded beneath the black plastic; there, they rose by 4–5 °C over bare soil and by at least 10–15 °C over the ambient air temperature. This helps drive out weeds but also increases evaporation from the soil surface, exposing the plant to stress and lowering output.

Vegetative growth parameters of green beans

The maximum fresh weight of 25.4 g plant^{-1} was achieved in growth season 2023 with the 50% IRg PRD & CRSM treatment, followed by 50% IRg PRD & RSM and 100% IRg & CRSM of 22.1 g plant^{-1} and 21.0 g plant^{-1}, respectively, while the lowest fresh weight of 9.7 g was reported under 75% IRg & UC in the first growing season (Fig. 9A). In growth season 2022, the greatest dry weight was 5.8 g plant^{-1} under the 50% IRg PRD & CRSM treatment, followed by the 50% IRg PRD & RSM and 100% IRg & CRSM treatments with 5.6 and 5.4 g plant^{-1}, respectively, while the minimum dry weight was 2.0 g plant^{-1} under the 75% IRg & UC treatment (Fig. 9B).

In 2022, the highest plant height measured under 50% IRg PRD & CRSM was 45.87 cm, while the lowest plat height was 18.30 cm under 50% IRg & UC. The following growing season showed a similar trend, but with higher plant height values: the highest plant height measured 48.27 cm under 50% IRg PRD & CRSM, followed by 100% IRg & CRSM with 48.13 cm without a significant difference, and the lowest plat height measured 32.97 cm under 50% IRg & UC (Fig. 9C).

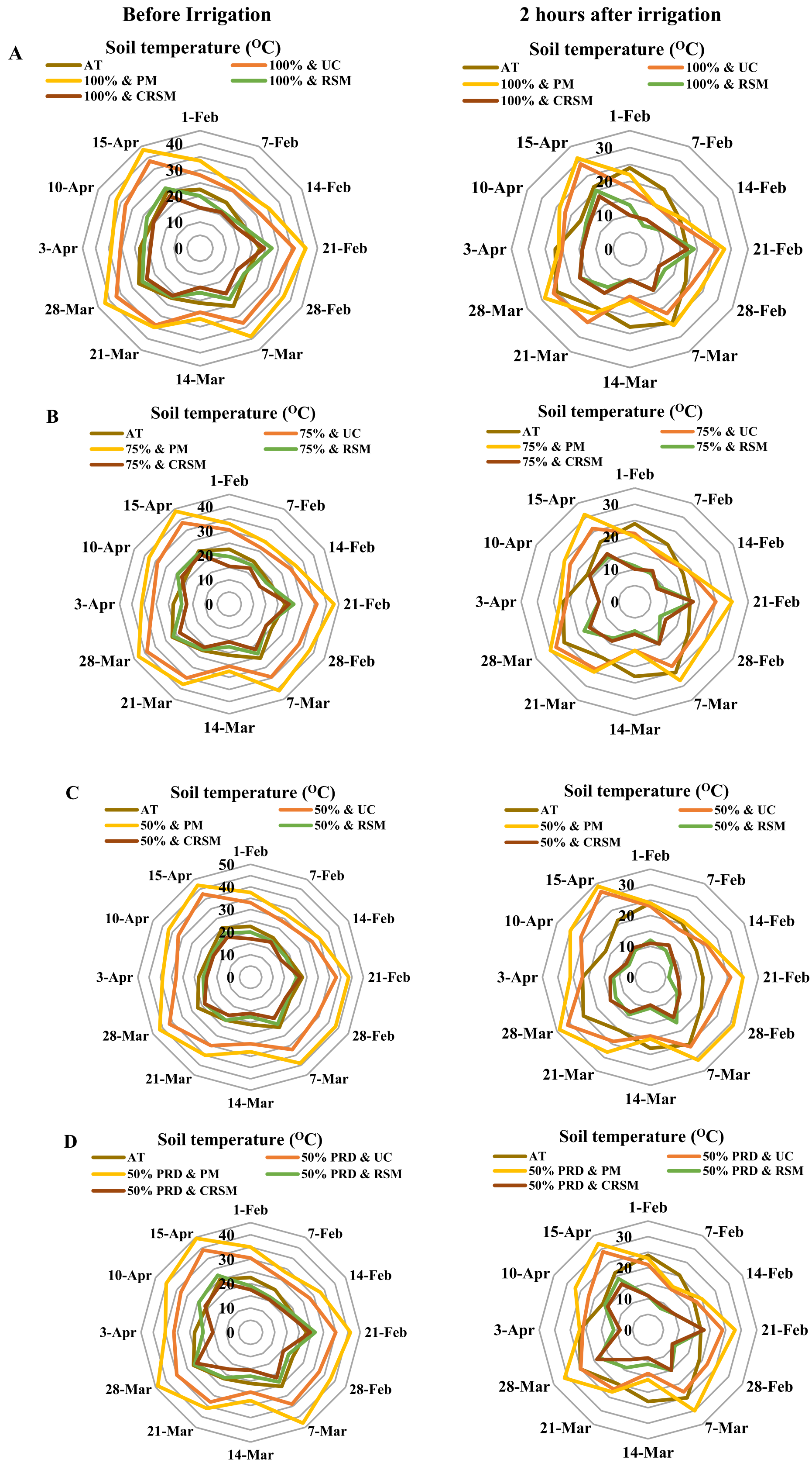
In 2022, the greatest leaf area value was 70.6 cm^2, reached under the 50% IRg PRD & CRSM treatment and 100% IRg & CRSM treatment with the same value, while the lowest leaf area value was 66.8 cm^2, recorded at 75% IRg & US by 35.4 cm^2. In 2023, the maximum leaf area value was 71.3 cm^2, achieved at 50% IRg PRD & CRSM, followed by 100% IRg & CRSM at 67.7 cm^2 and 100% IRg & CRSM at 67.4 cm^2. In comparison, for 75% DI and UC, the lowest leaf area value was 36.8 (cm^2) (Fig. 9D).

The maximum chlorophyll content under 50% IRg PRD & CRSM in 2022 was 0.33 mg L^{-1}; the lowest plat height was 0.21 mg L^{-1} under 50% IRg & UC. The second growing season followed the same trend, but with a higher chlorophyll content; the maximum plant height was 0.35 mg L^{-1} under 50% IRg PRD & CRSM followed by 100% IRg & CRSM with 0.33 mg L^{-1}; the lowest plat height was recorded under 50% IRg & UC and it was 0.23 mg L^{-1} (Fig. 9E). There were no significant differences between experimental treatments for chlorophyll values.

The 50% IRg PRD & CRSM treatment produced the highest pod weight value in 2022, 5.80 g plant^{-1}, which was followed by 50% IRg & RSM with 5.60 g plant^{-1}. The 50% IRg & UC treatment produced the lowest pod weight value, 2.0 g plant^{-1}. In contrast, the maximum pod weight value of 6.20 g plant^{-1} was achieved under the 50% IRg PRD & CRSM treatment, followed by 50% IRg & RSM with 5.90 g plant^{-1} (Fig. 9F). The green bean pod weight continued to follow the same trend in 2023 with higher values.

The 50% IRg PRD & CRSM treatment produced the highest pod length value in 2022, 14.13 cm, which was followed by the 75% IRg & CRSM treatment with 14.07 cm. The 50% IRg & UC treatment produced the lowest pod length value, 9.83 cm (Fig. 9G). The green bean pod length continued to follow the same trend in

Fig. 8 Effect of interaction between deficit irrigation strategies and soil mulches on soil temperature before and after irrigation for different measures as an average of both growing seasons



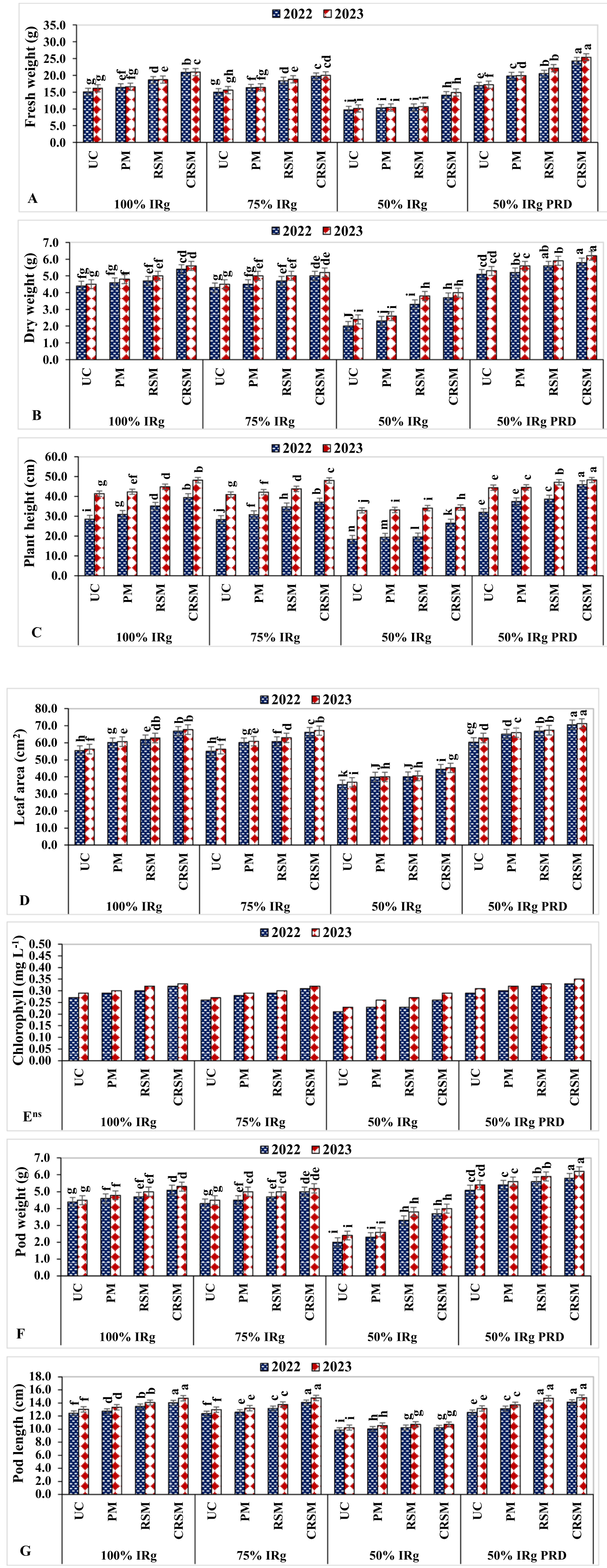


Fig. 9 The vegetative growth parameters of green beans under the interaction of experimental treatments for both growing seasons (**A**: Fresh weight, **B**: Dry weight, **C**: Plat height, **D**: Leaf area, **E**: Chlorophyll, **F**: Pod weight, **G**: Pod length). Means followed by the different letters within each column significantly differ according to the Duncan multiple comparison test at the 5% level.ach value is the average of three replicates over two seasons. ns: non-significant

2023 with higher values. In contrast, the maximum pod length value of 14.83 cm was achieved under the 50% IRg PRD & CRSM treatment, followed by 75% IRg & CRSM with 14.77 cm. The lowest leaf area value of 2.40 g was recorded at 50% IRg & UC by 10.23 cm (Fig. 9G).

Nutritional elements

In the first growing season, the maximum nitrogen content (N) in pods was observed at 2.24% with 100% IRg & CRSM, and the minimum was recorded at 1.57% with 75% IRg & UC. The maximum was followed by 2.14% with 50% IRg PRD & CRSM. The lowest value of nitrogen content was 1.47% recorded with 75% IRg and UC; there was little variation across the treatments in both growing seasons. The maximum nitrogen content in pods was 2.26% recorded with 100% IRg & CRSM in 2023, followed by 50% IRg PRD & CRSM with 2.24% (Fig. 10A).

In the first growing season, the maximum phosphorus content (P) in pods was observed at 0.34% with 100% IRg & CRSM, followed by 0.32% with 50% IRg PRD & CRSM. The lowest value of phosphorus content was 0.13% recorded with 50% IRg & UC. On the other hand, in 2023 the maximum phosphorus content in pods was 0.32% recorded with 100% IRg & CRSM, followed by 50% IRg PRD & CRSM with 0.31%, while the lowest phosphorus content was 0.13% under 50% IRg & UC (Fig. 10B).

The potassium (K) level in pods was found to be as high as 3.17% when treated with 100% IRg & CRSM in 2023, and as low as 1.53% when treated with 50% IRg & UC. These results were followed by 3.15% when treated with 50% IRg PRD & CRSM (Fig. 10C).

Microorganism's activity within the root zone

In both growing seasons, the maximum and minimum number of microorganisms were observed under 50% IRg & UC. In growth season 2022, the maximum total number of microorganisms was $2.8*10^8$ CFU per mL^{-1} of bacterial culture under the 50% PRD & CRSM treatment, followed by the 100% IRg & CRSM and 50% IRg PRD & RSM treatments, with $2.5*10^7$ and $2*10^7$ CFU per mL^{-1} of bacterial culture, respectively, while the minimum was $2.1*10^4$ under the 50% IRg & UC treatment (Fig. 11). In 2023, the 50% PRD & CRSM treatment had the highest total number of microorganisms ($3.2*10^8$ CFU per mL^{-1}), followed by the 100% IRg & CRSM and 50% IRg PRD & RSM treatments, which had $3.1*10^7$ and $2.2*10^7$ CFU per mL^{-1} of bacterial culture, respectively, and the minimum of $2.1*10^4$ was obtained under 75% IRg & UC (Fig. 11).

Quality parameters

Changes in microbial community activities and structure, as a result of applying soil organic mulch, can be used as early indicator of soil "health" and "quality" since soil microbial communities play a critical role in the recovery, which was reflected in an increase in the soil content of nutrients and their availability to the plant, and so in the quality of green beans through two criteria protein and fiber percentage. Although the differences between the treatments in protein were not significant, the differences between the percentages of fiber under the different treatments were significant.

In green bean pods, the highest percentage of fiber content (11.03%) was recorded in 2022 using 100% IRg & CRSM, followed by 10.99% for 50% IRg PRD & CRSM, while the lowest percentage of fiber content (4.69%) was measured using 50% IRg & UC. In 2023, 100% IRg & CRSM recorded the highest percentage of fiber content (11.23%), which was followed by 50% IRg PRD & CRSM (11.02%), while 50% IRg & UC recorded the lowest percentage of fiber content (4.81%) (Table 4).

In 2022, 100% IRg & CRSM had the highest protein content of 13.97% in green bean pods, followed by 50% IRg PRD & CRSM at 13.63%, and 75% IRg & UC had the lowest fiber level of 10.0%. In the same context, the highest protein content in 2023 was 14.07% with 100% IRg & CRSM, followed by 13.93% with 50% IRg PRD & CRSM, while the lowest fiber content was 10.23% with 75% IRg & UC (Table 4).

Cluster analysis and correlation study

The two-way cluster analysis and the resulting dendrogram based on deficit irrigation treatment and soil mulch revealed that the dendrogram for vegetative growth, soil, and irrigation parameters is divided into four groups (Fig. 12). The two-way cluster analysis and generated dendrogram based on the 15 measurements clearly categorized them into four groups (A, B, C, and D), while the UC, PM, RSM, and CRSM treatments were inserted into groups A, B, C, and D, respectively (Fig. 12).

In accordance with this, each of the four groups (A, B, C, and D) is further subdivided into four subgroups, each of which contains one of the following: 100% IRg & UC, 100% IRg & PM, 100% IRg & RSM, 100% IRg & CRSM; 75% IRg & UC, 75% IRg & PM, 75% IRg & RSM, 75% IRg & CRSM; 50% IRg & UC, 50% IRg & PM, 50% IRg & RSM, 50% IRg & CRSM; 50% IRg PRD & UC, 50% IRg PRD & PM, 50% IRg & RSM, and 50% IRg PRD & CRSM; respectively. A positive impact is indicated by the color red, and a negative impact by the color blue.

The results of the two-way cluster analysis also show that the 50% IRg PRD & CRSM (D-4) and 50% IRg PRD

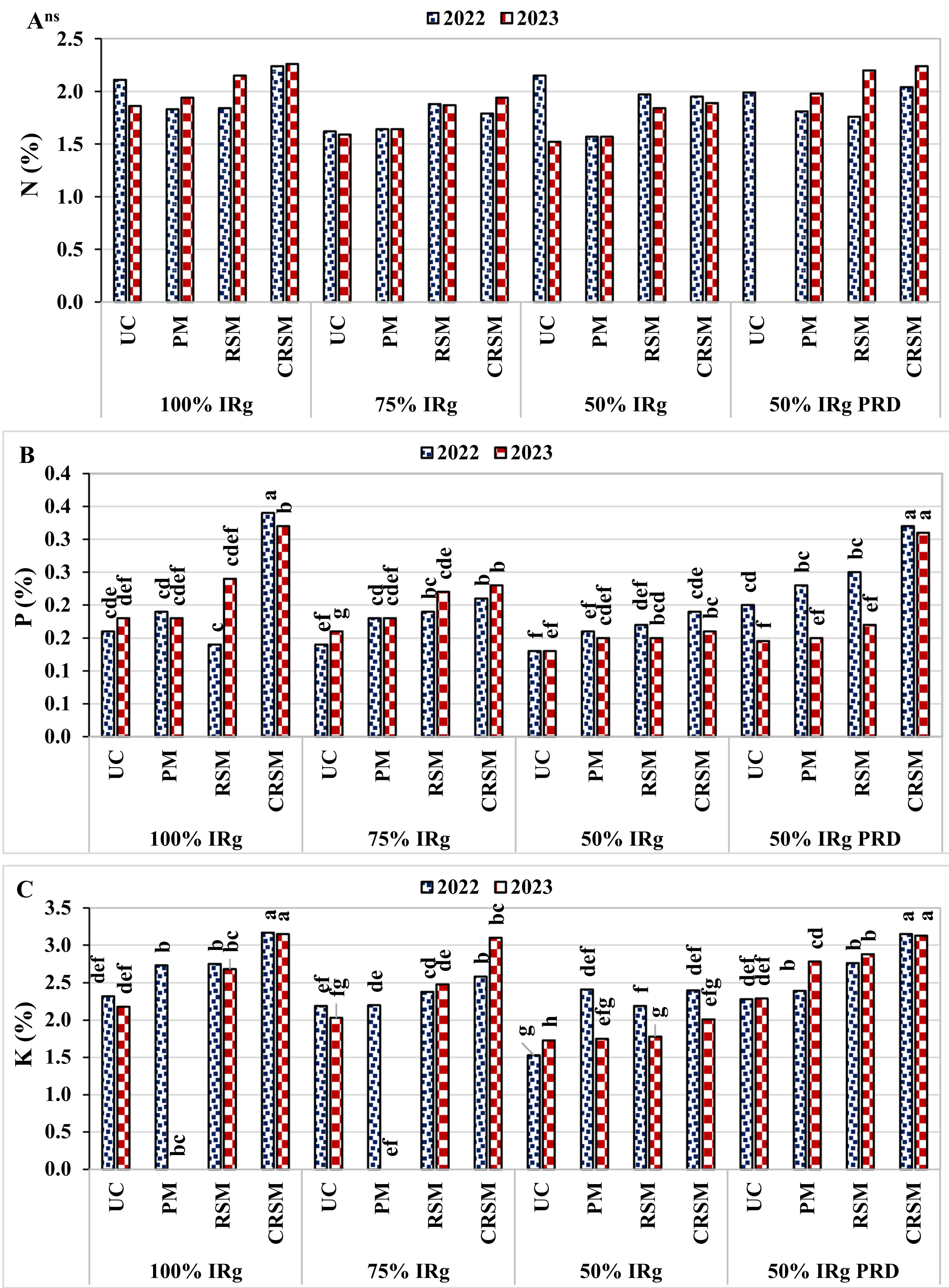


Fig. 10 The nutritional elements parameters of green beans **A** N (%), **B** P (%), and **C** K (%) under the interaction of experimental treatments for both growing seasons. Means followed by the different letters within each column significantly differ according to the Duncan multiple comparison test at the 5% level. Each value is the average of three replicates over two seasons. ns: non-significant

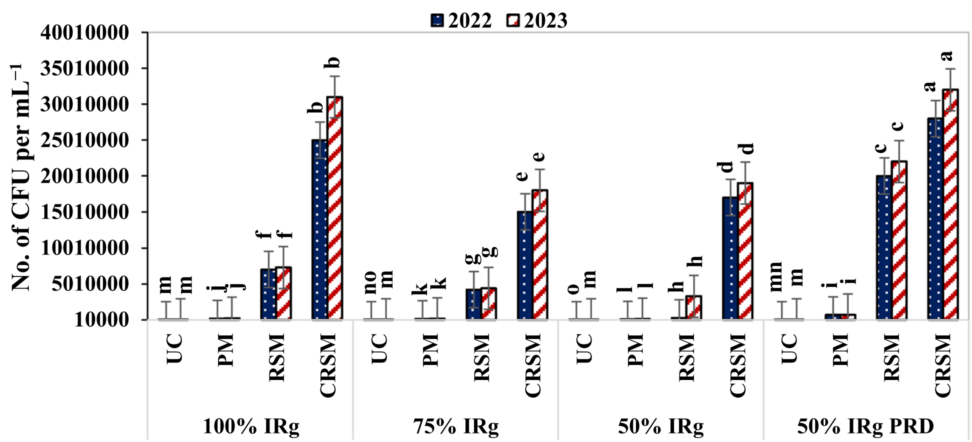


Fig. 11 The number of colony-forming bacterial units (CFU) under the interaction of deficit irrigation strategies and soil mulches treatments. Means followed by the different letters within each column significantly differ according to the Duncan multiple comparison test at the 5% level. ach value is the average of three replicates over two seasons. The number of colony-forming bacterial units (CFU) per gram (or milliliter) in the sample

Table 4 The percentage of protein and fiber content in the green bean pods

Deficit irrigation	Soil mulch	Protein content (%)		Fibers (%)	
		2022	2023	2022	2023
100% IRg	UC	12.47	12.53	8.88 g	8.96 g
	PM	11.70	11.73	9.09 e	9.16 f
	RSM	12.43	13.63	10.37 b	10.37 c
	CRSM	13.97	14.07	11.03 a	11.23 a
75% IRg	UC	10.00	10.23	7.14 k	7.17 k
	PM	10.13	10.30	7.77 j	7.85 ij
	RSM	11.63	11.70	7.92 i	7.98 i
	CRSM	11.70	11.73	8.98 f	9.10 fg
50% IRg	UC	11.83	12.03	4.69 m	4.81 l
	PM	10.23	10.40	7.00 l	7.18 k
	RSM	11.80	11.90	7.73 j	7.75 j
	CRSM	11.97	12.43	8.33 h	8.47 h
50% IRg PRD	UC	11.80	12.07	9.09 e	9.15 f
	PM	11.60	11.70	9.59 d	9.72 e
	RSM	12.87	12.90	9.98 c	9.98 d
	CRSM	13.63	13.93	10.99 a	11.02 a
LSD		NS	NS	0.0923	0.1767

Means followed by the different letters within each column significantly differ according to the Duncan multiple comparison test at the 5% level

Each value is the average of three replicates over two seasons

NS, non-significant

& RSM (D-3) treatments have a positive effect on the parameters that were studied (IWP, No. of CFU, Total Chl., fresh weight, dry weight, N, P, K, and yield). In contrast, the 50% IRg & UC (C-1), 50% IRg & PM (C-2), 50% IRg & RSM (C-3), and 50% IRg & CRSM (C-4) treatments have more negative effects on all studied measurements, with the exception of IWAE and IWP (Fig. 12).

Similarly, as Fig. 13 illustrates, Pearson's correlation analysis was utilized to ascertain the positive and negative connection between the parameters under investigation. The results of a Pearson's correlation study demonstrated a positive link between irrigation water productivity (IWP) and yield, leaf area, fresh weight, dry weight, plant height, pod weight, total chlorophyll, N. P., K., and CFU, as well as with fibers, protein, soil temperature (ST), IWAE, and fiber content. On the other hand, there is a negative correlation between IWP and pod length, soil moisture content (SMC), and irrigation water applied (IWA) (Fig. 13).

Feasibility study

From the economic analysis of irrigation system with compacted rice straw mulch, it was found that the highest net farm income was obtained under 50% IRg PRD & CRSM where the fixed costs (FC) were 1296.52 US\$ y^{-1}, while the variable costs (VC) were 1805.87 US\$ y^{-1}. Therefore, the total costs per year were 3102.39 US\$ y^{-1}, the total revenue (TR) 19,123.0 US\$ y^{-1} where it was calculated according to the Egyptian Ministry of Investment and Foreign Trade, General Organization for Export and Import Control commerce where the export price for green beans in 2023 was 2140 US\$ ton^{-1} and so the net farm income (NFI) equal to 16,020.61 US\$ y^{-1}, while the lowest NFI was detected under PM with 11,140.43 US\$ y^{-1} where the increase in price of plastic mulch decreases the net revenue (Table 5).

This proves the effectiveness of environmentally sustainable systems in preserving the environment while achieving a remunerative return for the farmer that encourages the continued adoption of these measures that preserve the natural resources of the agricultural process, namely water through the application of scarce irrigation, and soil using organic soil mulches made from rice straw, which performs two main actions: reducing evaporation from the soil and contributing to the provision of irrigation water, in addition to inhibiting weed growth and

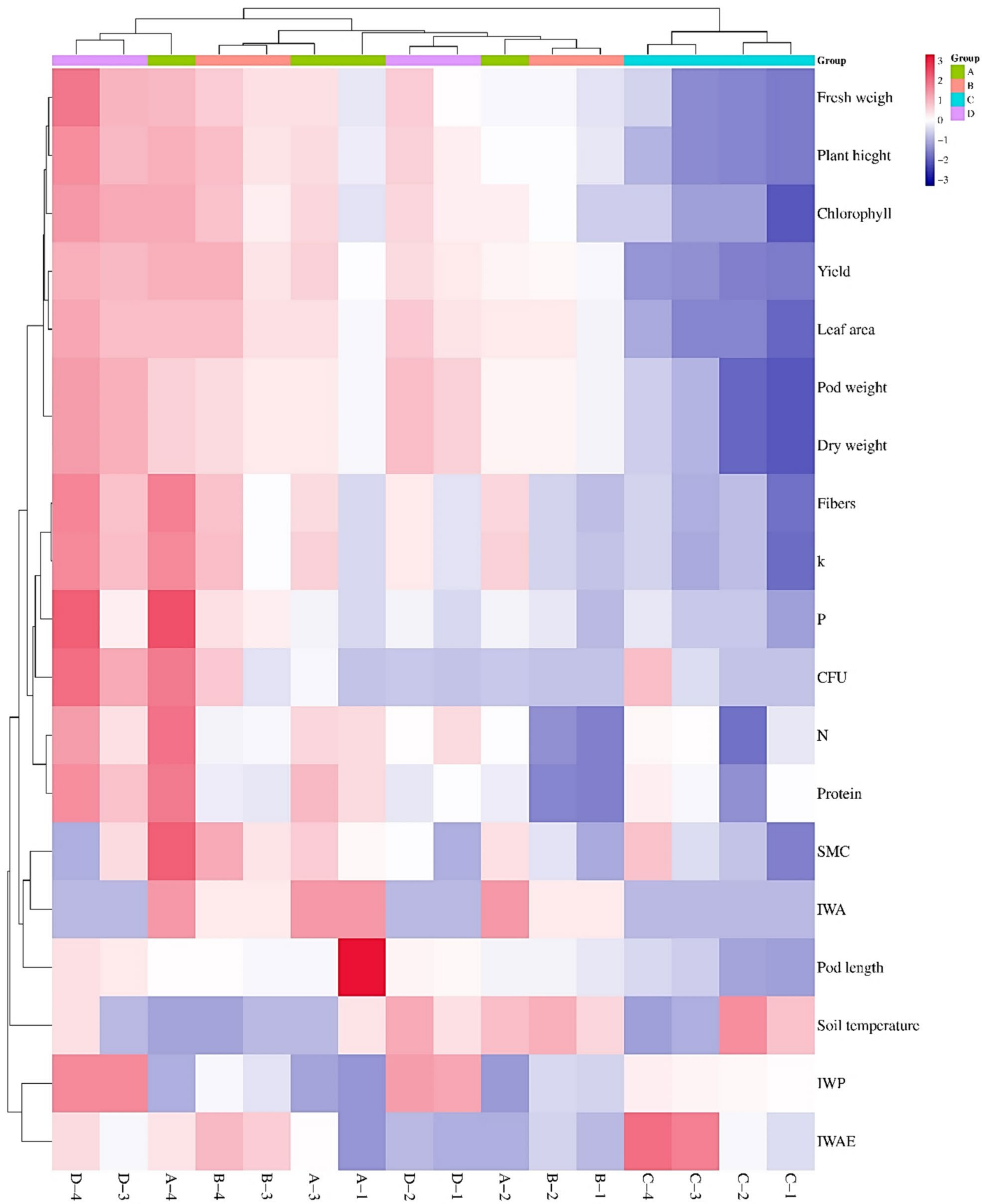


Fig. 12 Dendrogram of two-way cluster analysis of deficit irrigation and soil mulch treatments. CFU, colony-forming bacterial units, SMC, soil moisture content, IWAE, irrigation water application efficiency, IWA, irrigation water applied, and IWP, irrigation water productivity

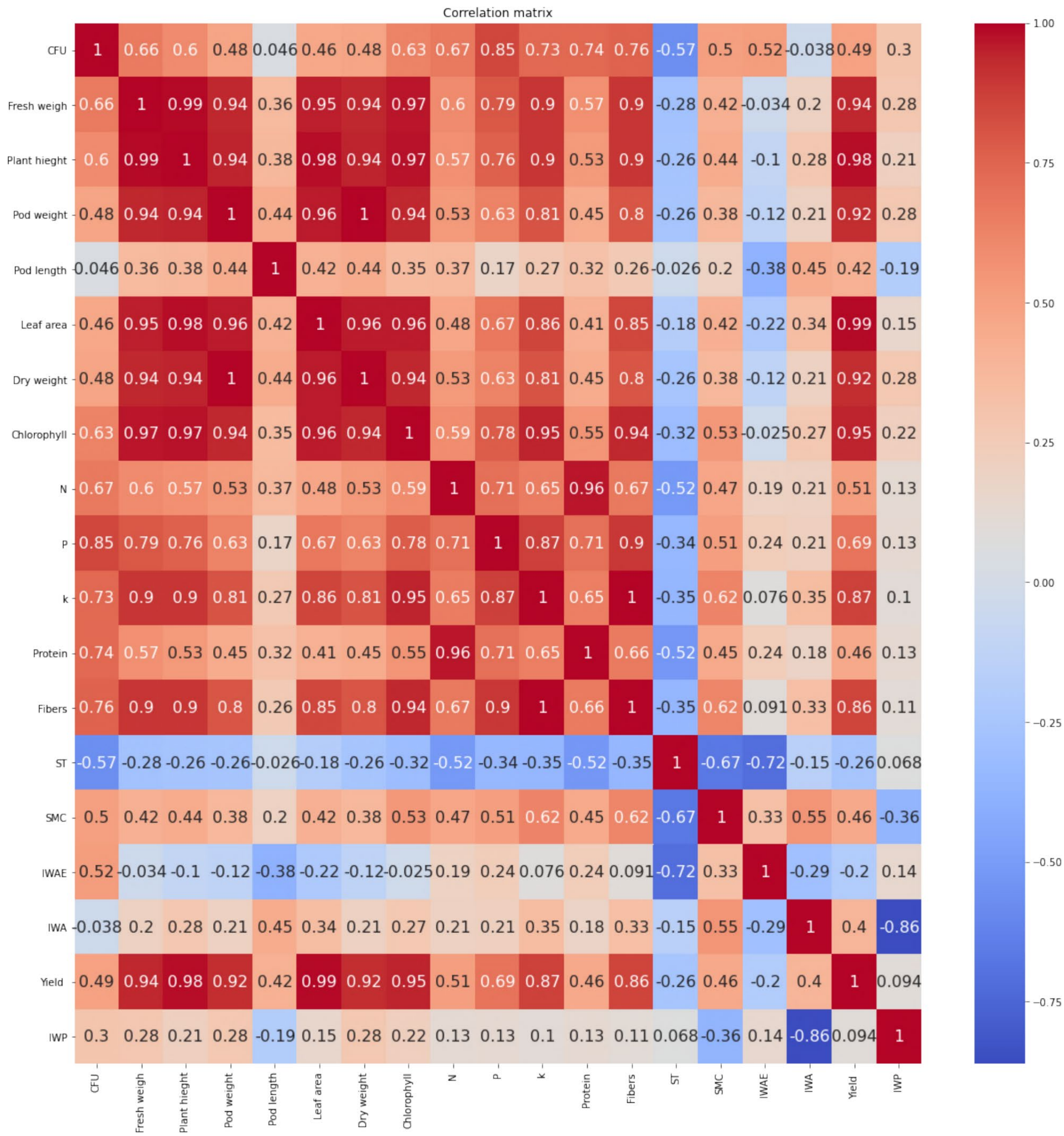


Fig. 13 Pearson's correlation matrix between vegetative growth, quality, soil, and irrigation parameters of green beans plants treated with deficit irrigation and soil mulch. CFU, colony-forming bacterial units, ST, soil temperature, SMC, soil moisture content, IWAE, irrigation water application efficiency, IWA, irrigation water applied, and IWP, irrigation water productivity

providing irrigation water in another way. In addition, rice straw, as an organic material, contributes to increasing the soil's ability to conserve water and increasing soil fertility, which increases green beans productivity.

Discussions

The results of yield (Fig. 6B) are in consistent with Abd El-Wahed et al. (2017) who illustrated the substantial impact of mulching materials, drip deficit irrigation, and

Table 5 Economic feasibility analysis for calculation of the net income of irrigation systems with organic mulch

Item		Costs (US\$ ha^{-1})		
		PM	RSM	CRSM
Fixed costs (FC)	Administrative expenses	148.50	148.50	148.50
	Annual consumption 10% (without land rent)	198.02	198.02	198.02
	Rent (on season)	950.00	950.00	950.00
Total FC		**1296.52**	**1296.52**	**1296.52**
Variable costs (VC)	Irrigation	237.40	237.40	237.40
	Seedlings	94.99	94.99	94.99
	Fertilizers	178.03	178.03	178.03
	Soil mulches	3523.52	261.95	117.76
	Weed control	235.53	235.53	235.53
	Harvesting	235.53	235.53	235.53
	Maintenance (2.2–7.4% FC)	678.31	678.31	678.31
Total VC		**5211.63**	**1950.06**	**1805.87**
Total revenue (TR)	Yield (ton ha^{-1})	8247.0	8714.0	8936.0
	Price (2140 US\$ ton^{-1})	17,649.0	18,647.96	19,123.00
Net farm income (NFI) = TR – TC		11,140.43	15,401.38	16,020.61

mulch layer thickness on crop yield. In the same context these outcomes are consistent with the observations made by Ajibola and Amujoyegbe (2019), who noted a marked enhancement in sesame yield (185 kg ha^{-1}) in plots mulched with elephant grass, while the control group yielded the lowest (57 kg ha^{-1}). Furthermore, Adesina et al. (2014) documented a significant increase in yield with dry grass mulch compared to no mulch. These outcomes are consistent with those of Parmar et al. (2013), who discovered that applying mulching material greatly increased the watermelon fruit yield. The significant effects of organic mulching on crop production, agronomic productivity, and microclimate were emphasized by Kader et al. (2017). In the "on" year, treatments with sub-soil plastic mulch with circular cuts, woodchips mulch, barley residue mulch, and sub-soil plastic mulch with wide cuts increased yield by 29.2%, 28.7%, 19.8%, and 10.5% compared to non-mulched, respectively. In the "off" year, treatments did not significantly affect variations in yield.

Because of their increased penetration, increased retention capacity, and ability to limit weed growth, organic mulch application has been shown to be especially successful at preserving soil moisture, which in turn promotes optimal crop development and greater yield outcomes. By increasing the barrier to water vapor flow between the soil surface and the atmosphere, mulch effectively reduces evaporation. Using plastic mulch can maximize crop output and water use efficiency (Coelho et al. 2022). Compared to fields covered with mulch, fields without mulch have higher losses from evapotranspiration (Biswas et al. 2022). This study demonstrates how mulch can increase soil moisture levels during the crop's main growing season; soil moisture levels in mulched fields are consistently higher than those in unmulched areas.

It has been demonstrated that using mulch to increase the resistance to water vapor transfer between the soil surface and the atmosphere is an effective way to minimize evaporation. Furthermore, as Adesina et al. (2014) have shown, using plastic mulch has the potential to increase agricultural output and improve water consumption efficiency.

The compression that rice straw undergoes reduces interstitial distances even further, making it more effective in lowering evaporation and air movement beneath the covers. This keeps ground humidity at high levels that approach field capacity even though there has been a 25–50% decrease in water quantities in some areas. However, the soil did not significantly change following irrigation, lessening the crop's negative effects from water shortages (Fig. 7). This is in relation to what compressing rice straw does by bringing the advantages of plastic wraps closer to organic wraps. This is in addition to what plastic wraps cannot provide, which is that rice straw is first and foremost an organic material that helps increase the fertility of the soil and increases the strength of the soil to retain water, which is reflected in its soil water holding capacity. Water stress under scarce irrigation while giving productivity almost like irrigation with 100% water of water needs, in addition to being environmentally safe, which makes it a sustainable method for managing irrigation water under water stress and water shortage.

The primary and most conspicuous aspect pertains to the efficacy of the 50% IRg PRD & CRSM treatment in significantly upholding ground moisture and mitigating airflow beneath the covering, achieving a high level of effectiveness, potentially surpassing the anticipated level. Conversely, the incorporation of rice straw into organic fertilizers contributes to enhancing the soil's capacity for water retention. This was evident in the consistent moisture levels across various measurements during the growth period, notably observed in the second season of 2023. Following the initial season, the soil was tilled with a mixture of rice straw covers, leading to improved soil fertility and enhanced water conservation capabilities. This enhancement was particularly pronounced in the experimental sandy soil (Fig. 7C, D).

In the current research, akin to prior studies, the use of plastic and organic mulches enhanced the soil's water content (Liu et al. 2009, 2014; Zhang et al. 2011; Zribi et al. 2015). Conversely, our findings contrast with Awodoyin et al. (2007) who noted that plastic mulches, particularly up-soil plastic mulch, resulted in the highest soil water content due to their superior ability to control evaporation compared to organic mulches and bare soil. Our results, however, demonstrate that the highest soil moisture levels were observed under CRSM > RSM > PM, with organic mulches acting as a protective layer that reduces water loss through evaporation from the soil surface, consequently boosting soil moisture content. Moreover, these organic mulches function as an organic fertilizer, enhancing the soil's water retention capacity. The CRSM treatment further restricted air movement through the straw, thereby reducing evaporation and increasing soil moisture content, maintaining levels below 50% IRg PRD & CRSM, near 75% IRg & CRSM, and 100% IRg & CRSM, with a moisture content decrease of approximately 1–2%.

The comparison of soil temperature variations before and after irrigation draws attention to the impact of irrigation in mitigating soil temperature and alleviating thermal stress on plants in the root zone. This analysis not only underscores the importance of irrigation in reducing heat stress on plants but also emphasizes the efficacy of Controlled-Release Soil Moisture (CRSM) in minimizing plant stress, thereby decreasing temperatures beneath the cover and ultimately lowering water loss due to evaporation from the soil surface. Conversely, the implementation of deficit irrigation strategies influenced soil mulches differently, with varying effects observed between organic and plastic mulches. As water stress intensified, soil temperatures tended to rise; however, this rise was least pronounced when CRSM was utilized. The differences in soil temperature under CRSM compared to those under 100% Irrigation Requirement (IRg) treatments were notably minimal, indicating the superior performance of Partial Root-Zone Drying (PRD) in mitigating crop water stress, reducing soil temperature, and minimizing evaporation losses from the soil surface, thus enhancing water management practices. The temperature differentials among the various irrigation water levels under 100% IRg and PRD ranged from 5 to 17%, underscoring the efficiency of PRD in maintaining optimal soil conditions. Remarkably, the Root-Soil-Moisture (RSM) system exhibited the lowest soil temperatures compared to 100% IRg, with variations of 6%, 27%, and 3% for the 75% IRg, 50% IRg, and 50% IRg PRD treatments, respectively, further highlighting its effectiveness in promoting sustainable water management practices (Fig. 8).

There were noteworthy connections observed within the realm of Precision Agriculture (PA) between crop yield and soil temperature, where the yield tended to decrease in cases where the soil temperature closely approached the temperature levels experienced under the Uncontrolled Condition (UC) treatment due to an excessive rise in soil temperature. Conversely, the soil temperature recorded under the Controlled-Release Surface Mulch (CRSM) treatment was notably lower than the atmospheric temperature, highlighting the impactful interplay between deficit irrigation techniques and soil mulching on the soil temperature dynamics. This interplay effectively mitigated water stress on the plant roots, thereby fostering enhanced growth and competitive advantage for winter-grown green beans against weed infestations by modulating the soil temperature and enhancing soil organic matter content, as illustrated in Fig. 8C, D.

These findings align with the research conducted by Nurzadeh Namaghi et al. (2018), which similarly demonstrated significant polynomial correlations between crop yield and soil temperature in the context of plastic mulching practices, leading to yield reductions in response to excessive soil temperature spikes reaching 36–37 °C within the 20–60 cm soil depth range under the up-soil plastic mulch (UPM) treatment. The elevated soil temperature levels in the UPM treatment were associated with heightened rates of flower bud and fruit shedding, alongside yield reductions attributed to diminished leaf nitrogen concentrations. Overall, the study results underscore the superiority of organic mulching techniques in arid and semi-arid regions utilizing pressurized irrigation systems, as they effectively regulate the phenomenon of alternate bearing, boost crop yield, and offer additional benefits such as soil organic matter enhancement, ease of availability and application, cost-effectiveness, and a reduced environmental footprint.

The daily maximum soil temperature was decreased by the mulching treatments, while the daily minimum soil temperature was increased compared to the bare treatment. This phenomenon can possibly be attributed to the fact that rice straw mulching has the effect of increasing the albedo of the soil and reducing the thermal conductivity of the soil surface, thereby diminishing the amount of solar energy that can penetrate into the soil as indicated by Li et al. (2013). This process also leads to a reduction in the dissipation of soil energy, ultimately resulting in a notable decrease in the daily soil temperature range.

Moreover, mulch serves as a protective buffer that helps to insulate the soil from both excessive heat and cold temperatures, as highlighted by Kader et al. (2019). Olasantan (1999) also noted that soil covered with mulch tends to exhibit higher temperatures during colder weather conditions and lower temperatures during warmer weather conditions compared to unmulched soil. Furthermore, findings by Wang et al. (2020) suggest that organic mulch plays a crucial role in moderating temperatures and safeguarding the soil and roots from extreme temperature fluctuations.

The outcomes pertaining to the vegetative growth parameters of green bean depicted in Fig. 9 are consistent with the findings of with Aniekwe and Anike (2015), who observed that mulched plots yielded plants with a higher number of vines, leaves, leaf area, and vine length for cucumber. Similar observations regarding plant growth parameters were also documented by Singh and Kamal (2012) in tomato plants, Mahadeen (2014) in summer vegetables like okra and squash, and in potato crops as reported by Kumar et al. (2015).

According to the assessments of N, P, and K levels in green beans, the findings indicated that there was no notable distinction between the 100% IRg & CRSM and 50% IRg PRD & CRSM, hence suggesting the potential utilization of 50% IRg PRD alongside compacted rice straw mulch as a water-saving measure (as illustrated in Fig. 10A–C). There is an absence of discernible disparities in the nutritional components present in the 100% IRg PRD & CRSM and 50% IRg PRD & CSRM treatments. This lack of variation can be attributed to the uniform application of the same type of fertilizer across all treatment groups. It is essential to acknowledge that an escalation in the volume of irrigation water administered results in the flushing out of essential fertilizer elements from the soil, rendering them inaccessible to the plants for absorption and utilization. Conversely, by reducing the volume of irrigation water added, there is a notable enhancement in the plant's capacity to assimilate and utilize the fertilizer components effectively. This phenomenon is underpinned by scientific principles, which elucidate that during periods of drought stress, plants tend to elongate their root systems in search of increased water and nutrient uptake, thereby maximizing their physiological functions. Consequently, the absence of conspicuous variations in the nutrient concentration between the 100% IRg PRD and 50% IRg PRD treatments is compounded by the supplementary role played by rice straw as an organic material rich in essential nutrients, albeit in modest quantities. Noteworthy is the positive impact attributed to the rise in soil water retention capacity coupled with diminished irrigation water inputs, resulting in an amplified utilization of fertilizer components by the plants.

This observation aligns with the study by Nurzadeh Namaghi et al. (2018), which emphasized that organic mulches present superior choices in arid and semi-arid regions where traditional irrigation techniques are employed. Moreover, organic mulches were found to have a positive impact on the flowering and fruiting patterns as well as nut development in pistachio trees across different growth cycles. The enhancements noted in these aspects can be linked to the heightened concentrations of leaf nutrients such as N, P, and Mg, which play crucial roles in photosynthesis stimulation and overall tree progress. Furthermore, Sahin et al. (2016) highlighted that lettuce crops could be effectively irrigated with reduced water quantities to enhance mineral content and conserve water, albeit at a slightly lower water productivity level.

Nurzadeh Namaghi et al. (2018) documented that the utilization of mulching had a significant impact on the concentration of phosphorus in the leaves during the 'off' season and on nitrogen, phosphorus, and magnesium during the 'on' season. It was found that the highest levels of these essential nutrients were observed in the treatment involving mulch made from barley residues. This highlights the importance of mulching in influencing the nutrient composition of plants in different growing seasons, showcasing the potential benefits of using barley residues as mulch material for enhancing plant health and growth.

The scarcity of water leads to a reduction in the dilution of photo-assimilates by lowering the water content in the pods of green beans. This phenomenon promotes the accumulation of assimilates within the pods, ultimately enhancing the quality parameters of the produce (Kuscu et al. 2014; Chakma et al. 2021). Additionally, the temperature in the root zone plays a crucial role in regulating the transport of nutrients from the source to the sink during pod development and in the biochemical processes occurring during the ripening of green bean pods. Elevated temperatures have been shown to increase the protein and fiber content in the pods while simultaneously decreasing the acid content, indicating the intricate relationship between temperature and the nutritional composition of green beans (Mesa et al. 2022).

The application of rice straw mulch has been found to influence the development of microbial communities in the soil. By combining rice straw with nitrogen, phosphorous, and potassium, there was a significant shift in the composition of soil microbes. Furthermore, when the amount of rice straw was reduced along with nitrogen, phosphorous, and potassium, a similar effect on microbial communities was observed. This suggests that the presence of rice straw, in conjunction with essential nutrients, has a profound impact on the diversity and composition of soil microbes, highlighting the potential of using rice straw as a sustainable agricultural practice.

The findings regarding the microbial communities under various treatments, as presented in Table 4, align with the conclusions drawn by Ding et al. (2018). Their study emphasized that enhancing soil diversity through the enrichment of nutrients positively influenced crop yield. Specifically, the combined application of rice straw and balanced fertilizers was found to increase microbial diversity and enhance crop productivity compared to using rice straw alone. This approach not only aids in reducing straw waste but also contributes to the efficient cycling of nutrients in the soil, thereby promoting sustainable agricultural practices for improved crop yields and soil health.

In the realm of agricultural soil conservation, as highlighted by Kader et al. (2017), the utilization of organic mulching stands out as a crucial and impactful practice. This technique has transcended its traditional role and has witnessed a surge in popularity within urban settings, being extensively employed for purposes such as greenification and soil restoration to foster plant growth. Noteworthy is the fact that organic mulching goes beyond mere superficial changes in soil properties, encompassing alterations in temperature dynamics and bulk density. Furthermore, it serves as a valuable source of carbon and essential nutrients for the soil, thereby playing a pivotal role in shaping nutrient absorption mechanisms in plants.

Dotaniya et al. (2018) delved into the intricate effects of soil mulch on the rhizosphere environment, shedding light on the profound impact of mulching on microorganisms, which exhibit sensitivity to variables like soil temperature and moisture levels. The augmentation of microbial communities under the protective cover of rice straw mulch aligns with the findings of Liu et al. (2017), who expounded on how the surge in microbial populations and heightened enzymatic activities catalyze the breakdown of straw, consequently enhancing the overall quality of maize straw-amended soil. Whether it is rice straw or maize straw, the application of organic mulch has been proven to enhance the organic carbon content within the soil, thereby bolstering soil quality and ultimately leading to enhanced yields, albeit contingent on the specific soil type. The interplay between organic mulching and soil organic carbon concentration culminates in the formation of macro-aggregates and a subsequent increase in crop yield, underscoring the multifaceted benefits of this sustainable agricultural practice.

All of these outcomes in the same line of research results where the 50% IRg PRD & CRSM achieved highest CFU mL^{-1} because using the organic soil mulch increased the soil carbon content and increased consequently the soil moisture holding capacity and mitigated the effect of water stress, on the other hand rice straw mulch increased soil temperature which provided the suitable condition for the growth of microorganisms by providing appropriate heat and a lack of soil, paving the way for the diversity of populations. On the other hand, minimizing evaporation and transpiration through controlling weeds and covering increased water intrusion while decreasing water loss, which made 50% IRg PRD & CRSM mulch the appropriate mulch for soil moisture conservation and sustainable green beans production. Reversely, the treatment 50% IRg & UC recorded the lowest CFU mL^{-1} as a result of the lack of soil mulch, which accelerates the process of losing water through evaporation from the soil surface and thus exposes the crop to water stress. In addition, the lack of soil mulch made the gas exchange between the air and the soil high, especially at night, which exposes the plant to frost and a decrease in the crop yield.

Conclusions

The green beans under the 50% IRg—PRD & CRSM treatment enhanced soil organic content and preserved soil moisture.

By reducing the irrigation water application by half, the 50% IRg—PRD & CRSM approach demonstrated an increase in green bean yield and water productivity. Therefore, it is recommended to apply 50% IRg—PRD & CRSM in regions with limited water availability, where the primary benefit of partial root drying deficit irrigation lies in its maximization of water productivity.

The research suggests expanding the adoption of organic soil mulching in conjunction with 50% IRg—PRD for various other winter crops especially crops sensitive to water shortages and crops located in water stressed areas due to its positive impact on water conservation, and enhancement of crop yield and quality.

In addition, there is a need to conduct more research on using agricultural wastes, of which rice straw is widely available in Egypt and transforming those wastes into environmentally friendly amendments.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

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