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RESEARCH ARTICLE

Optimizing maize yield and kernel quality *via* leguminous green manure intercropping with deficit irrigation in arid agroecosystem

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Highlights

- In leguminous green manure intercropping system, 15% deficit irrigation can achieve maize yield equivalent to conventional irrigation.
- It also enhanced kernel quality and sustained high levels of protein and nutrients under deficit irrigation.
- These improvements were attributed to an increased net photosynthetic rate and a greater soil nitrogen supply.

Abstract

Intercropping with leguminous green manure represents a sustainable approach to enhance agroecosystem resilience through improved soil fertility and resource-use efficiency. However, the synergistic mechanisms between leguminous green manure intercropping and regulated deficit irrigation in maintaining maize yield stability and enhancing kernel profiles under arid conditions remain inadequately understood. A three-year (2021–2023) split-plot field experiment incorporated main plots consisting of three green manure incorporation practices: full green manure incorporation (M||V-P), green manure stubble retention (M||V-R), and maize without green manure (maize sole cropping, SM); while split plots comprised three irrigation regimes: conventional (I3; 400 mm), 15% deficit (I2; 340 mm), and 30% deficit (I1; 280 mm). The study examined maize grain yield, kernel quality (protein, fat, starch, and essential amino acid content), net photosynthetic rate (Pn) of maize, and soil nitrate-ammonium nitrogen content. M||V-P and M||V-R increased maize grain yield compared to SM, with M||V-P producing 5.7% higher yields than M||V-R. Notably, M||V-PI2 achieved comparable yield to M||V-PI3 while reducing irrigation by 15%, demonstrating an 18.3% yield increase over SMI3. M||V-P and M||V-R enhanced kernel quality compared to SM, exhibiting higher protein, fat, starch, and essential amino acid content. Decreased irrigation led to increased kernel protein content but reduced fat and starch contents. The kernel protein content under M||V-PI2 showed no significant difference from M||V-PI1, while maintaining fat, starch, and essential amino acid content similar to M||V-PI3. M||V-PI2 improved all kernel quality parameters relative to SMI3. These enhancements primarily resulted from maize intercropped with leguminous green manure in combination with 15% deficit irrigation, which increased maize Pn by 14.3%, and elevated soil nitrate-ammonium nitrogen by 12.5 and 5.2%, respectively. These findings demonstrate a scalable approach for sustainable maize production though the integration of leguminous green manure intercropping in water-limited regions.

Keywords: intercropping with leguminous green manure, yield–water tradeoff, kernel quality, maize

1. Introduction

Global food security faces increasing challenges from climate change and water scarcity, particularly in arid regions, which comprise 41% of global agricultural land (Chen *et al.* 2024). Additionally, agricultural product quality has received heightened attention due to its vital role in human and animal health (D'Amzto *et al.* 2019; Zhu *et al.* 2021). Maize, a fundamental crop for both food and feed, serves an essential function in maintaining livestock production and enhancing living standards, requiring innovative approaches to optimize

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yield and quality under water-limited conditions (Yu *et al.* 2022). Traditional monoculture systems often deplete soil nutrients and increase water requirements, while diversified cropping systems, particularly intercropping with leguminous green manure, offer complementary benefits through nitrogen fixation, improved soil structure, and enhanced water-use efficiency (Cheng *et al.* 2018; Liu *et al.* 2022; Zheng *et al.* 2022).

Green manure, serving as an effective organic fertilizer and soil enhancement material, has broad applications in contemporary agriculture (Yu *et al.* 2024). During flowering, shallow rotary tillage incorporates green manure into the soil, delivering multiple agroecological advantages (Hu *et al.* 2023; Yang *et al.* 2023). Research demonstrates that green manure cultivation improves soil nutrient availability, including inorganic nitrogen, available potassium, and organic matter, while enhancing soil structure (Yang *et al.* 2023; Li *et al.* 2024). Furthermore, green manure enhances soil aggregate cementation, water stability, and moisture-retention capacity (Iderawumi and Kamal 2022; Singh *et al.* 2023). Research indicates that green manure implementation can increase soil water content by 10.3–13.0% (Daryanto *et al.* 2018). These integrated effects ensure adequate water and nutrient availability for crop growth, supporting consistent and high grain production (Zhang *et al.* 2013; Wu *et al.* 2023). Green manure's beneficial effects are well-documented across various crop production systems. In paddy fields, sustained green manure application increases soil inorganic nitrogen and organic matter, enhancing rice quality through improved straight-chain starch, protein, fat, and essential amino acid content (Wang *et al.* 2021). In arid irrigation areas, multiple cropping green manure improves wheat grain protein and wet gluten content by increasing soil organic matter and inorganic nitrogen (Zhang *et al.* 2023). Moreover, green manure cultivation enhances maize grain quality by optimizing amino acid composition and balance, while increasing mineral element content, including calcium and cobalt (Marques *et al.* 2018; Li J Z *et al.* 2023).

Intercropping green manure with major crops presents an efficient strategy that enhances soil nitrogen supply while reducing ground surface evapotranspiration in the cultivated layer (Li *et al.* 2021). This approach improves soil moisture retention while moderating excessive consumption by high-demanding crops, enhancing water use efficiency in the intercropping system (Yin *et al.* 2020). Although intercropping may result in higher total evaporation and reduced soil moisture (0–50 cm) due to extended growing periods, it demonstrates lower daily evaporation rates compared to monoculture, indicating significant short-term water conservation potential (Franco *et al.* 2018; Gong *et al.* 2020). Irrigation optimization remains crucial for maximizing water use efficiency in intercropping systems (Yin *et al.* 2020; Liu *et al.* 2025). Therefore, empirical research must evaluate how reduced-irrigation green manure intercropping systems can maintain crop yield stability while improving product quality.

Although green manure application enhances soil organic matter, nutrient availability, and moisture retention, further investigation is needed regarding the combined effects of green manure intercropping systems with precision irrigation on maize grain yield and kernel quality (Ma *et al.* 2025). This research proposes that combining maize and legume green manure intercropping with regulated deficit irrigation will: (1) sustain maize yield stability, and (2) improve kernel quality through enhanced photosynthetic efficiency and soil nitrogen dynamics. To evaluate these hypotheses, a three-year field experiment was conducted in an arid region of Northwest China. This investigation provides comprehensive analysis of these interactions, contributing valuable insights for sustainable agricultural practices in water-limited environments.

2. Materials and methods

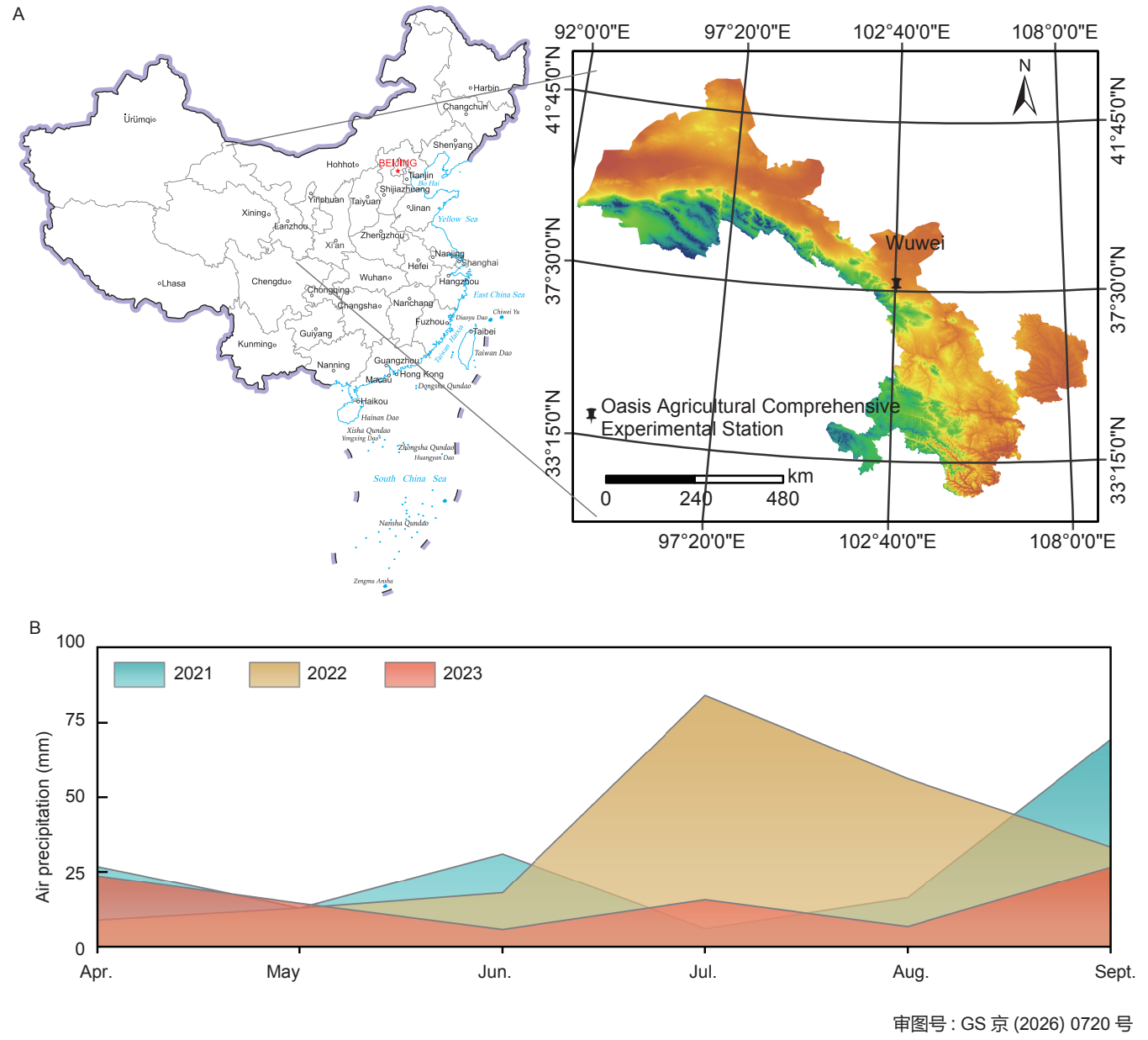
2.1. Site description

The field experiment was conducted at the Oasis Agricultural Comprehensive Experimental Station of Gansu Agricultural University, China (Fig. 1-A). The site is situated in a cold-temperate arid climatic zone, receiving average annual precipitation below 180 mm, predominantly between July and September. The mean annual temperature is 7.3°C, with accumulated temperature above 10°C reaching approximately 3,000°C. The region exhibits high aridity indices, characterized by annual potential evapotranspiration exceeding 2,400 mm, sunshine duration of 2,945 h, and solar radiation of 6,000 MJ m^{-2}. These conditions establish the area as a typical inland arid irrigated agricultural district, where single-season crop maturity is achievable, while dual-season crop maturities remain limited. The soil comprises a thick layered irrigation-silted soil with the following characteristics in the top 30 cm: soil pH of 8.3, total nitrogen content of 0.78 g kg^{-1}, total phosphorus content of 1.4 g kg^{-1}, available phosphorus content of 29.2 mg kg^{-1}, rapidly available potassium content of 152.6 mg kg^{-1}, and organic matter content of 15.2 g kg^{-1}. The air precipitation during the crop growth period for 2021–2023 is shown in Fig. 1-B.

2.2. Experimental design and management

The three-year experiment (2021–2023) employed a split-plot design with three replicates. The main split comprised three green manure incorporation practices: full green manure incorporation (M||V-P), green manure stubble retention (M||V-R), and maize without green manure (maize sole cropping, SM); the split plot consisted of three irrigation regimes: conventional (I3; 400 mm), 15% deficit (I2; 340 mm), and 30% deficit (I1; 280 mm). Each experimental plot measured 7 m×6 m (length×width).

Maize (*cv*. Xianyu 335) was sown on 23 April, 2021, 18 April, 2022, and 21 April, 2023, with corresponding harvest dates of 23 September, 2021, 20 September, 2022, and 24 September, 2023. The leguminous green manure, common vetch (*cv*. Sujian 3), was annually sown on 1 April and mechanically crushed with a straw return crusher before being shallowly rotated and incorporated into the soil on 27 June, 2021, 25 June, 2022, and 23 June, 2023, to a depth of 15 cm. The intercropping system utilized a strip configuration with maize-to-common vetch width ratios of 110 cm:70 cm (Fig. 2-A). The intercropping system of maize–leguminous



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Fig. 1 The geographical location (A) and precipitation patterns (B) of the Oasis Agricultural Comprehensive Experimental Station of Gansu Agricultural University, China during crop growing seasons from 2021 to 2023.

green manure belt alternates planting between years to prevent potential continuous cropping defects. Field plots were separated by 50 cm wide and 30 cm high ridges to minimize cross-plot water movement. Common vetch was sown in the intercrop strip at 75 kg ha^{-1} with 20 cm row spacing, while maize planting density was maintained at 82,500 plants ha^{-1} with 40 cm row spacing. Within-row plant spacing varied between systems: 30 cm for maize sole cropping and 18.5 cm for intercropped maize. All maize strips received polyethylene film mulching, which was mechanically recovered using a mulch recycling machine post-harvest following stalk removal.

Considering the naturally high potassium content of the experimental soil, fertilization was limited to nitrogen (N) and phosphorus (P) applications. The conventional N fertilizer application rate (urea with 46-0-0 of N-P_2O_5-K_2O) was 360 kg ha^{-1}, distributed in three applications: 30% as basal dose at sowing, 50% at the V12 stage (12th leaf stage), and 20% at the R2 stage (blister stage). P fertilizer (diammonium phosphate with 18-46-0 of N-P_2O_5-K_2O) was applied as a single basal dose at 180 kg ha^{-1}. Irrigation was administered through 7.5 cm diameter flexible pipes, with a water-flowmeter installed at the discharging end to regulate and record irrigation volume. Detailed irrigation schedules and quantities are presented in Table 1. All other field management practices followed established protocols for precise high-yield cultivation.

2.3. Determination of indexes and calculations

Grain yields Each plot was harvested after the maize R6 (physiological maturity) stage. The grains underwent air-drying under ambient conditions, cleaning to remove

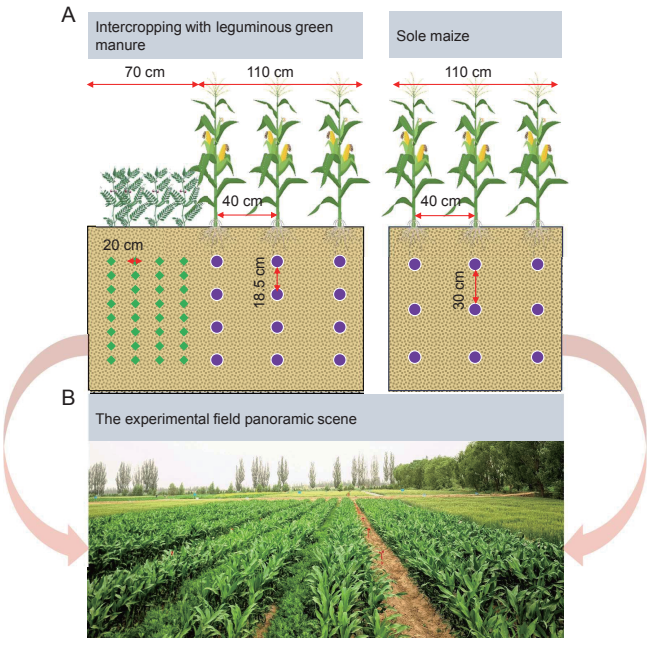


Fig. 2 Schematic diagrams (A) and panoramic view of the experimental field (B).

impurities, and subsequent weighing. The grain yield was standardized to 14% moisture content using a Portable Moisture Analyzer (PM-8188, Kett Electric Lab., Tokyo, Japan).

Maize kernel nutritional quality At the R6 stage, 10 representative maize plants were randomly sampled from each plot. The plants were manually threshed and naturally air-dried. The kernel quality parameters (protein, fat, and starch contents) were analyzed using a Foss Multi-Function Near-Infrared Analyzer (NIRS DS-2500, FOSS, Denmark).

For amino acid analysis, maize grain powder sample (100 mg) was weighed and transferred into a 2 mL microcentrifuge tube. Each sample underwent extraction with 1 mL of aqueous solution containing hydrochloric acid (0.5 mol L^{-1}), followed by vertexing at 8,000 r min^{-1} for 20 min, and ultrasonic-assisted extraction in a temperature-controlled water bath (25°C, 20 min). The extracts were centrifuged at 20,000×g for 20 min to separate particulate matter. For analysis, 250 μL of the supernatant was carefully transferred to a liquid chromatography sample vial and diluted to 1 mL with 80% acetonitrile aqueous.

Quantitative analysis was conducted using high-performance liquid chromatography-inductively coupled plasma mass spectrometry (HPLC-ICP-MS, AGILENT, United States) equipped with an Agilent Infinity Lab Poroshell 120 HILIC-Z column (2.1 mm×100 mm, 2.7 μm). The mobile phase consisted of phase A, an aqueous solution of 20 mmol L^{-1} ammonium formic acid (pH=3), and phase B, a mixture of acetonitrile/water (9:1) containing 20 mmol L^{-1} ammonium formic acid (pH=3). The flow rate and injection speed were set at 0.50 mL min^{-1} with the injection temperature maintained at 25°C. Ammonium formic acid (pH=3) was dissolved in acetonitrile/water (9:1) solution. The flow rate, column temperature, injection volume, and total run time were 0.50 mL min^{-1}, 25°C, 1 μL, and 15 min respectively. The elution conditions are shown in Table 2.

Net photosynthetic rate (Pn) During vegetative tassel (VT), silking (R1), and blister (R2) stages of maize, measurements were taken on clear days between 9:00 a.m. and 11:30 a.m. Five maize plants with uniform growth were randomly selected from each plot. The Pn was measured at the midpoint of the ear leaf using a Li-6800 portable photosynthesis system tester (Li-COR Inc., USA). Measurements avoided leaf veins and edges. The system utilized a red-light source, with photosynthetically active radiation in the leaf chamber set to 1,200 μmol m^{-2} s^{-1}, leaf chamber temperature maintained at 25°C, CO_2 concentration controlled at 400 μmol mol^{-1}, and relative humidity set at 50%. Three stable readings were recorded per leaf, with the mean value used for subsequent analysis.

Soil nitrate-ammonium nitrogen During the maize VT, R1, and R2 stages, soil samples were collected from four depth intervals (0–20, 20–40, 40–60, and 60–80 cm) using a soil auger. The samples were air-dried, sieved through a 0.2 mm sieve, and stored for analysis. For each measurement, 5.00 g of sample was precisely weighed using an electronic balance and transferred into a 200 mL flask. The sealed flask containing the sample was supplemented with 50 mL of KCl solution (2 mol L^{-1}) before undergoing agitation on a shaker at constant temperature for 1 h. After agitation, the suspension settled for 5 min before filtration through filter paper; the defined filtrate aliquots were analyzed using the SmartChem 450 Automatic Intermittent Chemical Analyzer (1900108S, AMS, France).

Comprehensive evaluation Simplified correlation analysis and principal component analysis were performed on the evaluation indicators, and 12 original indicators under 9

Table 1 Irrigation allocation for the crop growing season

Irrigation stages[1)]	Irrigation quota (mm)					
	30% deficit irrigation (I1)		15% deficit irrigation (I2)		Conventional irrigation (I3)	
	Maize sole cropping	Maize–common vetch intercropping	Maize sole cropping	Maize–common vetch intercropping	Maize sole cropping	Maize–common vetch intercropping
V3/V1 stage	50	50	60	60	70	70
R2/V6 stage	60	60	75	75	90	90
VT stage	60	60	75	75	90	90
R1 stage	55	55	65	65	75	75
R2 stage	55	55	65	65	75	75

[1)] V3, 3rd leaf stage of common vetch; V1, 1st leaf stage of maize; R2, branching stage of common vetch; V6, 6th leaf stage of maize; VT, tasseling stage of maize; R1, silking stage of maize; R2, blister stage of maize.

treatments underwent downgrading (Tang *et al.* 2021). The fuzzy mathematical membership function method determined the membership function values of each treatment indicator. These selected indicators were averaged and utilized for comprehensive ranking based on their average value. A higher average value indicated a higher ranking (Li *et al.* 2022). The calculation formula of the membership function is as follows:

$$\mu(X_i)=(X_i-X_{min})/(X_{max}-X_{min}) \quad (1)$$

$$\mu(X_i)=1-(X_i-X_{min})/(X_{max}-X_{min}) \quad (2)$$

where $\mu(X_i)$ represents the transformed value of an indicator's original data using the membership function; X_i is the original measured value of the indicator, and X_{max} and X_{min} are its maximum and minimum values, respectively.

2.4 Statical analysis

Statistical analyses were conducted using IBM SPSS Statistics 26.0 (SPSS Inc., Chicago, IL, USA), incorporating one-way ANOVA and multiple comparisons performed with Duncan's method (α=0.05). Figures were created using Origin 2021 (OriginLab Corporation, Northampton, MA, USA) and ArcMap 10.8 (ESRI, USA).

3. Results

3.1. Grain yield

Cropping patterns, irrigation levels, and their interactions significantly affected grain yield (Fig. 3). Maize grain yield increased 9.4–28.3% through M||V-P, and 8.4–26.5% through M||V-R compared to SM. Furthermore, maize grain yield with M||V-P increased by 6.4–7.3% under I2 and 5.8–9.6% under I3 compared to M||V-R. While maize grain yield in SM decreased with reduced irrigation quota, no significant difference was observed between I2 and I3 in maize grain yield with M||V-P and M||V-R. Notably, M||V-PI2 achieved comparable yields to M||V-PI3, while demonstrating increases of 5.0–7.9 and 15.4–19.2% compared to M||V-RI3 and SMI3, respectively. These findings indicate that intercropping with green manure can compensate for yield reduction caused by moderately reduced irrigation. Specifically, maize intercropping with leguminous green manure combined with full incorporation maintains maize yield under 15% deficit irrigation.

Table 2 Optimization of gradient elution conditions for accurate determination of amino acid

Time (min)	Mobile phase B (%)
0.0	100
11.5	70
12.0	10

3.2. Kernel nutritional quality

Protein, fat, and starch Cropping patterns and irrigation levels significantly affected kernel protein, fat, and starch content, while their interaction significantly influenced only protein content (Table 3). Kernel protein content increased by 10.8–16.1% through M||V-P, and 4.4–9.5% through M||V-R compared to SM. Additionally, kernel protein content increased 5.8–6.5% through M||V-P compared to M||V-R. As irrigation quota decreased, kernel protein content showed an increasing trend, though no significant difference appeared between I2 and I1 (SM only performed in 2021). Notably, the protein content with M||V-PI2 showed no significant difference from M||V-PI1, while achieving 4.1–5.2 and 9.9–10.3% increases over M||V-RI1 and SMI1, respectively. These results demonstrate that intercropping with leguminous green manure effectively enhances kernel protein content, with this effect amplified under reduced irrigation.

Compared to SM, kernel fat content increased 8.0–18.3% through M||V-P, and 5.2–7.7% through M||V-R. Moreover, kernel fat content increased 4.0–10.9% through M||V-P (2022 and 2023) relative to M||V-R. Among different irrigation quotas under M||V-P conditions, the fat content of I1 was 4.2–7.7% lower than I3; however, no significant difference emerged in kernel fat content between M||V-PI2 and M||V-PI3, which showed increases of 4.8–10.9 and 11.2–18.3% compared to M||V-RI3 and SMI3, respectively. These

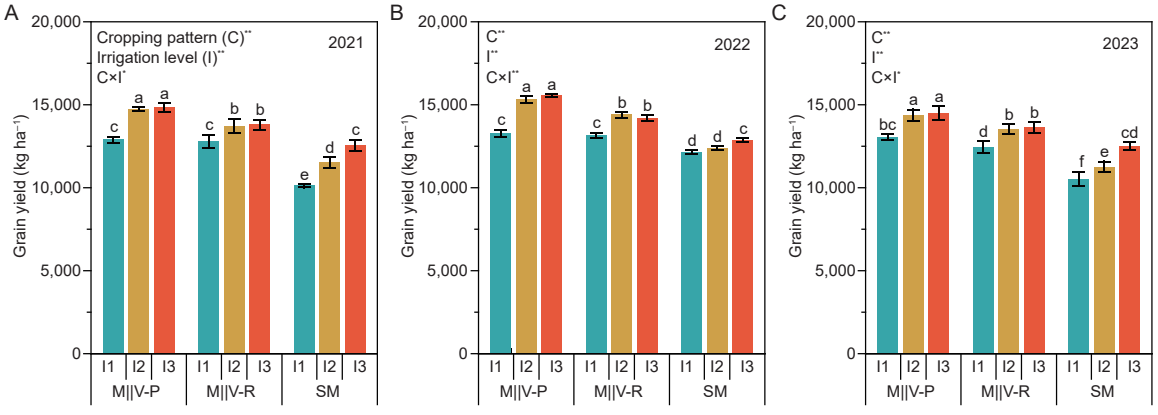


Fig. 3 Maize grain yield varies according to cropping patterns and irrigation levels. M||V-P, maize intercropping with leguminous green manure combined with full incorporation; M||V-R, maize intercropping with leguminous green manure combined with stubble retention; SM, maize sole cropping. I1, 280 mm (30% deficit irrigation); I2, 340 mm (15% deficit irrigation); I3, 400 mm (conventional irrigation). The error bars indicate the standard errors (n=3). Lowercase letters above the bars indicate significant differences between treatments at P<0.05. ** and * indicate that the effects of the factors on the index are significantly different at the probability levels of 0.01 and 0.05, respectively.

findings suggest that intercropping leguminous green manure with full incorporation under 15% deficit irrigation achieves comparable fat content to conventional irrigation.

The kernel starch content increased 5.4–6.4% through M||V-P, and 2.2–3.0% through M||V-R compared to SM. Additionally, kernel starch content under M||V-P significantly exceeded M||V-R. No significant difference in kernel starch content appeared across both M||V-R (2021) and SM (2022) under varying irrigation levels. While I1 irrigation reduced kernel starch content in M||V-P compared to I3, no significant difference emerged between M||V-PI2 and M||V-PI3, which exceeded SMI3. These results indicate that intercropping with leguminous green manure enhances kernel starch content effectively, with full return practice and 15% deficit irrigation achieving kernel starch content equivalent to conventional irrigation.

Essential amino acids Kernel phenylalanine (Phe), leucine (Leu), and methionine (Met) content were significantly influenced by cropping patterns and irrigation levels, while their interaction showed no significant effect on these parameters (Table 4). Compared to SM, kernel Phe, Leu and Met content increased by 4.7–5.7, 6.8–8.5, 7.0–9.0% in M||V-P, and by 3.3–3.7, 5.7–7.0, 4.4–5.0% in M||V-R, respectively. Additionally, M||V-P demonstrated higher kernel Phe, Leu, and Met content than M||V-R. Notably, M||V-PI1 exhibited the highest Phe, Leu, and Met content, while M||V-PI2, M||V-PI3, and M||V-RI1 showed no significant differences. M||V-PI2 demonstrated increases of 3.0 and 6.8% in Phe content, and 3.0% and 10.3% in Leu content compared to M||V-RI3 and SMI3, respectively.

The ANOVA results indicated significant effects of cropping patterns and irrigation levels on kernel threonine (Thr), isoleucine (Ile), valine (Val), and lysine (Lys) content (Table 4). The kernel Thr, Ile, Val, and Lys content increased by 3.0–4.0, 4.2–7.9, 6.3–13.2, 3.5–6.4% in M||V-P, and by 2.0–2.5, 2.5–4.3, 5.0–10.6, 2.5–5.2% in M||V-R compared to SM, respectively. M||V-P exhibited higher kernel Thr, Ile, Val, and Lys content than M||V-R. Compared to SMI3, kernel Thr, Ile, and Val content significantly increased under SMI1, while Lys content decreased. Furthermore, M||V-PI1 showed the highest Thr, Ile, and Val content, with M||V-PI2, M||V-PI3, and M||V-RI1 showing no significant differences, while M||V-PI2 increased Thr, Ile, and Val content by 2.0, 4.0, 6.3% and by 4.4, 8.3, 14.7% compared to M||V-RI3 and SMI3, respectively. M||V-PI3 exhibited the maximum Lys content, with M||V-PI2, M||V-PI1, and M||V-RI3 showing no significant differences.

Cropping patterns significantly influenced kernel tryptophan (Try) content, while irrigation levels and their interactions showed no significant effect (Table 4). Compared to SM, both M||V-P and M||V-R demonstrated increases in grain Try content by approximately 3.5–5.7 and 2.5–3.6%, respectively. Additionally, M||V-P exhibited higher grain Try content than M||V-R. The highest kernel Try content was observed in M||V-PI2, showing a 5.0% increase compared to SMI3.

Table 3 Effects of cropping patterns and irrigation levels on kernel protein, fat, and starch composition

Cropping patterns[1)]	Irrigation levels[2)]	Protein (%)	Fat (%)	Starch (%)
2021				
M||V-P	I1	6.96 a	3.69 bc	68.44 b
	I2	6.90 ab	3.75 ab	68.98 a
	I3	6.80 b	3.85 a	69.09 a
M||V-R	I1	6.56 c	3.59 c	66.90 c
	I2	6.48 cd	3.65 bc	67.10 c
	I3	6.40 d	3.68 bc	67.16 c
SM	I1	6.28 e	3.42 d	64.95 e
	I2	6.16 ef	3.44 d	65.21 de
	I3	6.13 f	3.47 d	65.38 d
2022				
M||V-P	I1	7.04 a	3.54 b	69.21 b
	I2	6.93 ab	3.74 a	69.95 a
	I3	6.85 b	3.83 a	70.18 a
M||V-R	I1	6.65 c	3.37 c	67.05 d
	I2	6.54 cd	3.42 bc	67.55 c
	I3	6.47 d	3.46 bc	67.73 c
SM	I1	6.28 e	3.13 d	65.58 e
	I2	6.07 f	3.23 d	65.87 e
	I3	5.90 f	3.24 d	65.93 e
2023				
M||V-P	I1	7.11 a	3.70 b	69.46 b
	I2	7.07 a	3.84 a	70.16 a
	I3	6.95 b	3.90 a	70.27 a
M||V-R	I1	6.73 c	3.56 d	67.61 d
	I2	6.67 c	3.62 cd	67.95 c
	I3	6.56 d	3.65 bc	68.08 c
SM	I1	6.41 e	3.35 f	65.83 f
	I2	6.24 f	3.42 ef	66.16 e
	I3	6.14 f	3.46 e	66.24 e
Significance (*P*)				
Cropping patterns (C)		**	**	**
Irrigation levels (I)		**	*	**
C×I		*	ns	ns

[1)] M||V-P, maize intercropping with leguminous green manure combined with full incorporation; M||V-R, maize intercropping with leguminous green manure combined with stubble retention; SM, maize sole cropping.

[2)] I1, 280 mm (30% deficit irrigation); I2, 340 mm (15% deficit irrigation); I3, 400 mm (conventional irrigation).

Different lowercase letters following values in the same column signify significant differences at $P<0.05$ between treatments within the same year. ** and * indicate that factor effects on the index are significantly different at the 0.01 and 0.05 probability levels, respectively. ns indicates no significant effect of factors on the measured parameter.

3.3. Net photosynthetic rate (Pn)

The Pn of maize was significantly affected by cropping patterns and irrigation levels; however, no significant interaction effect was observed between these factors (Fig. 4). Compared to SM, the Pn of maize increased by 9.6–33.6% in M||V-P, and by 5.2–23.3% in M||V-R. M||V-P demonstrated a more pronounced increase than M||V-R. The Pn under M||V-P and M||V-R at I1 was lower than at I3. Conversely, SM showed a progressive decline in Pn as irrigation quota decreased. The Pn of M||V-PI2 was comparable to M||V-PI3, while achieving 7.7–22.3% higher values than SMI3. These findings suggest that maize intercropped with leguminous green manure enhances maize Pn. Importantly, intercropping with leguminous green manure combined with full incorporation and 15% deficit irrigation maintains maize Pn without reduction.

Table 4 Essential amino acid content of kernel as affected by cropping patterns, and irrigation levels

Cropping patterns[1)]	Irrigation levels[2)]	Phe (mg kg^{-1})	Thr (mg kg^{-1})	Leu (mg kg^{-1})	Ile (mg kg^{-1})	Trp (mg kg^{-1})	Met (mg kg^{-1})	Val (mg kg^{-1})	Lys (mg kg^{-1})
2021									
M||V-P	I1	68.41 a	76.16 a	59.51 a	58.60 a	6.15 a	33.35 a	22.56 a	296.23 ab
	I2	68.36 a	76.13 a	59.50 a	58.59 a	6.21 a	33.26 a	22.55 a	298.78 a
	I3	67.82 ab	75.73 a	58.07 ab	57.86 ab	6.18 a	32.26 a	21.88 abc	298.98 a
M||V-R	I1	67.61 abc	75.31 ab	58.35 ab	57.54 abc	6.08 abc	32.77 a	22.19 ab	291.95 bc
	I2	67.28 bc	75.19 ab	57.80 ab	57.52 abc	6.14 a	32.32 a	22.10 ab	293.41 bc
	I3	66.99 c	74.63 bc	57.28 b	56.75 bcd	6.12 ab	31.80 a	21.00 bcd	296.16 ab
SM	I1	65.93 d	74.11 c	55.11 c	56.26 cd	5.94 c	30.83 c	20.67 cde	281.88 e
	I2	65.80 d	73.99 cd	54.54 c	55.98 d	5.98 bc	30.08 bc	19.98 de	285.71 de
	I3	65.15 d	73.03 d	53.65 c	54.40 e	5.96 c	29.39 bc	19.33 e	288.95 cd
2022									
M||V-P	I1	69.38 a	68.96 a	59.17 a	58.27 a	10.30 ab	38.71 a	26.53 a	270.04 ab
	I2	69.36 a	68.98 a	59.17 a	58.24 a	10.50 a	38.69 a	26.52 a	272.93 a
	I3	68.58 ab	68.50 ab	58.24 a	57.62 ab	10.33 ab	38.32 ab	25.51 ab	273.13 a
M||V-R	I1	68.28 ab	68.37 ab	59.12 a	57.54 ab	10.20 b	37.80 abc	26.16 ab	266.86 ab
	I2	67.92 ab	67.85 abc	58.80 a	56.85 abc	10.29 ab	37.15 bc	25.73 ab	268.23 ab
	I3	66.75 bc	67.60 bc	57.88 a	55.71 cd	10.24 b	36.32 cd	25.10 bc	269.31 ab
SM	I1	65.66 cd	67.37 bc	55.98 b	55.93 bcd	9.89 c	36.53 cd	24.97 bc	253.70 d
	I2	64.93 cd	66.79 cd	54.87 bc	54.81 de	9.93 c	36.44 cd	24.08 cd	259.53 cd
	I3	63.85 d	65.93 d	53.97 c	53.42 e	9.91 c	35.35 d	23.33 d	263.43 bc
2023									
M||V-P	I1	70.14 a	73.68 a	59.66 a	58.51 a	8.74 ab	37.15 a	24.96 a	277.57 ab
	I2	70.11 a	73.67 a	59.65 a	58.48 a	8.88 a	37.10 a	24.95 a	280.29 a
	I3	69.45 ab	73.24 ab	58.47 ab	57.81 a	8.77 ab	36.41 ab	24.11 abc	280.49 a
M||V-R	I1	69.20 abc	72.96 ab	59.06 ab	57.61 ab	8.66 b	36.41 ab	24.60 ab	273.84 bc
	I2	68.85 bc	72.64 abc	58.62 ab	57.26 abc	8.74 ab	35.86 bc	24.33 abc	275.25 abc
	I3	68.12 c	72.23 bcd	57.90 b	56.30 bcd	8.70 b	35.18 cd	23.47 bcd	277.16 ab
SM	I1	67.05 d	71.86 cd	55.87 c	56.16 cd	8.44 c	34.80 d	23.24 cd	262.22 e
	I2	66.62 de	71.51 de	55.02 cd	55.47 d	8.48 c	34.38 de	22.45 de	267.05 de
	I3	65.75 e	70.60 e	54.13 d	53.98 e	8.46 c	33.49 e	21.75 e	270.62 cd
Significance (*P*)									
Cropping patterns (C)		**	**	**	**	**	**	**	**
Irrigation levels (I)		**	*	*	**	ns	**	**	*
C×I		ns	ns	ns	ns	ns	ns	ns	ns

[1)] M||V-P, maize intercropping with leguminous green manure combined with full incorporation; M||V-R, maize intercropping with leguminous green manure combined with stubble retention; SM, maize sole cropping.
[2)] I1, 280 mm (30% deficit irrigation); I2, 340 mm (15% deficit irrigation); I3, 400 mm (conventional irrigation).
Different lowercase letters following values in the same column signify significant differences at $P<0.05$ between treatments within the same year. ** and * indicate that factor effects on the index are significantly different at the 0.01 and 0.05 probability levels, respectively. ns indicates no significant effect of factors on the measured parameter.

3.4. Soil nitrate-ammonium nitrogen content

Cropping patterns and irrigation levels significantly influenced soil nitrate-ammonium nitrogen content in the 0–40 cm soil layer, while cropping patterns demonstrated a significant effect on soil nitrate nitrogen content in the 40–60 cm soil layer (Fig. 5). The nitrate nitrogen content increased by 15.2–29.9, 12.3–31.7, and 9.5–18.0% in the 0–20, 20–40, and 40–60 cm soil layers respectively under M||V-P, and by 9.6–20.2, 10.3–25.6, and 2.4–6.1% under M||V-R, compared to SM. These findings indicate that intercropping with leguminous green manure effectively enhances soil nitrate-nitrogen content. Under reduced irrigation quota, the nitrate-nitrogen content of the 0–40 cm soil layer decreased in SM, with I1 showing significantly lower levels than I3 by 11.0–20.3%. However, irrigation levels in intercropping systems showed no significant differences in the 0–20 and 40–60 cm soil layers. The soil nitrate nitrogen content in the 20–40 cm layer decreased by 14.4–7.8% under M||V-R with I1 compared to I3.

The ammonium nitrogen content in the 0–20 and 20–40 cm soil layers increased significantly under M||V-P by 21.5–26.5 and 23.1–27.4%, and under M||V-R (I1 and I2) by 11.1–19.9 and 7.0–23.9%, respectively, compared to SM. Under reduced irrigation conditions, SM exhibited decreased soil ammoniacal nitrogen content, with reductions of 21.4–24.8% (I1) and 14.0–19.8% (I2) in the 0–40 cm soil layer compared to I3. Both M||V-P and M||V-R showed reductions under I1 compared to I3. However, intercropping systems showed no significant difference in soil ammoniacal nitrogen content between I2 and I3, suggesting that intercropping with leguminous green manure and 15% deficit irrigation maintains soil ammonia nitrogen content without significant depletion.

3.5. The correlation analysis of grain yield, kernel quality parameters, Pn, NO_3^--N, and NH_4^+-N

Maize grain yield demonstrated highly significant positive

correlations with Pn, NO_3^--N, and NH_4^+-N (P<0.01) (Fig. 6). Kernel quality parameters, including protein, fat, and starch contents, exhibited significant positive associations with Pn, NO_3^--N, and NH_4^+-N (P<0.01). Additionally, Phe, Leu, Lle, Met, and Val showed significant positive correlations with Pn and NO_3^--N (P<0.01). Trp demonstrated significant positive correlation with NO_3^--N, while Phe, Leu, and Lys showed positive associations with NH_4^+-N (P<0.01). Notable significant positive correlations were observed between maize grain yield and kernel protein, fat, starch, Leu, Lle, Met, and Val (P<0.01), as well as between grain yield and Trp, Lys (P<0.05).

3.6. Comprehensive evaluation

Principal component analysis (PCA) PCA was performed on 12 indicators per treatment to reduce data redundancy. Following the criterion of eigenvalue>1 and cumulative contribution rate>85.00%, two principal components were extracted. PC1 and PC2 explained 77.87 and 10.02% of the total variance respectively, achieving a cumulative contribution rate of 87.89% (Table 5). These extracted principal components effectively represented the majority of the original information, enabling compression of the initial indicators into two components. The first principal component exhibited an eigenvalue of 9.35, with high positive loadings for protein (0.96), fat (0.95), starch (0.93), Phe (0.91) and Thr (0.91). The second principal component showed an eigenvalue of 1.20, with positive loadings for Fat (0.25), Lys (0.38), Leu (0.19), Ile (0.46), and yield (0.55).

Analysis of the composite score per indicator For methodological clarity, the principal components PC1 and PC2 were designated as F_1 and F_2, respectively. Following established PCA methodology, the eigenvector for each principal component was calculated by dividing the initial

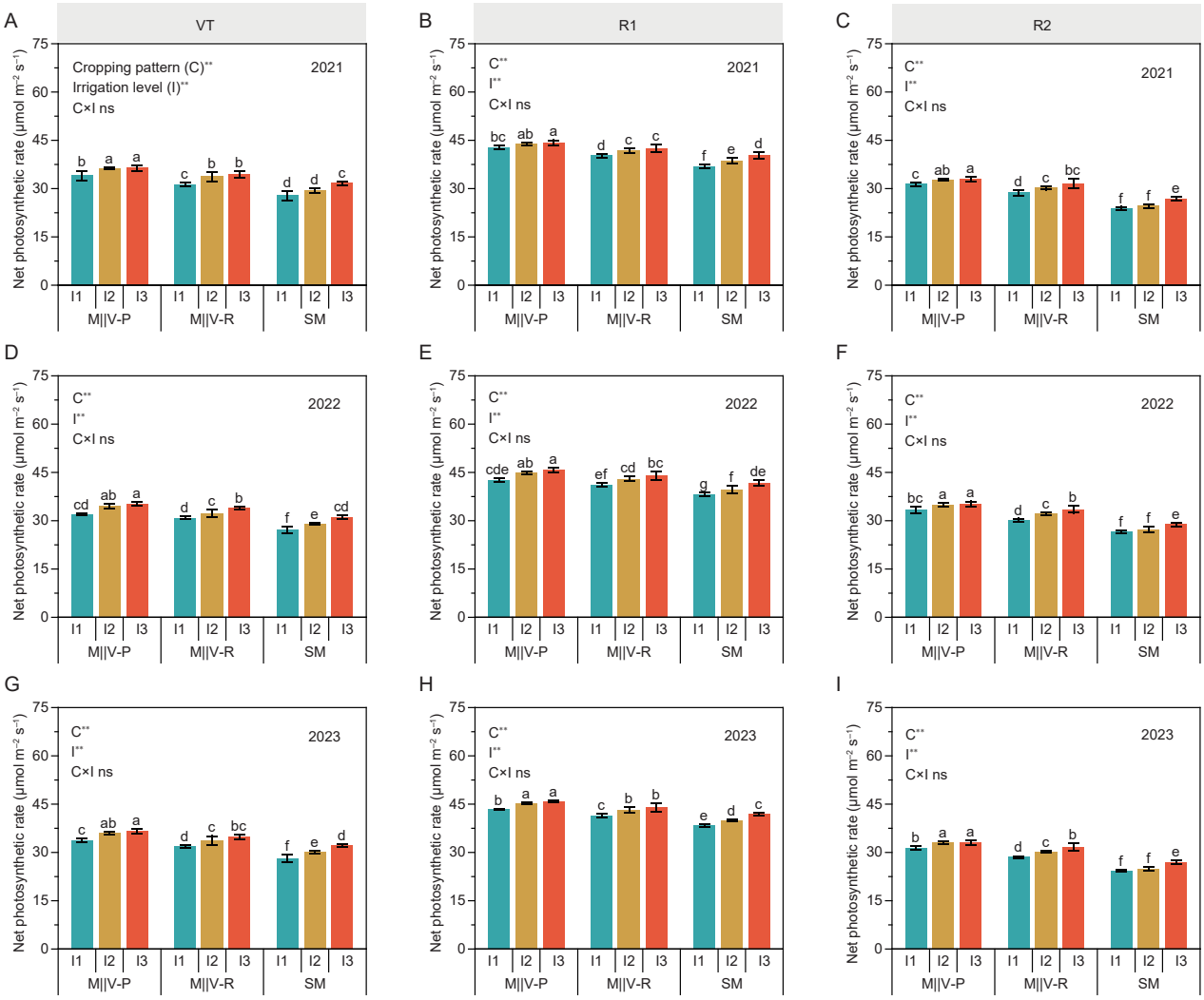


Fig. 4 Photosynthetic rates in maize vary according to cropping patterns and irrigation levels. M||V-P, maize intercropping with leguminous green manure combined with full incorporation; M||V-R, maize intercropping with leguminous green manure combined with stubble retention; SM, maize sole cropping. I1, 280 mm (30% deficit irrigation); I2, 340 mm (15% deficit irrigation); I3, 400 mm (conventional irrigation). VT, vegetative tassel; R1, silking stage; R2, blister stage. Error bars indicate standard errors (n=3). Lowercase letters above bars indicate significant differences between treatments at P<0.05. ** indicate that the effects of the factors on the index are significantly different at the 0.01 probability level. ns indicates that the factors have no significant effect on the index.

factor loading by the square root of its corresponding eigenvalue. The linear combination formula of the two principal components and the 12 indexes can be expressed as follows:

$F_1=0.31X_1+0.31X_2+0.31X_3+0.30X_4+0.30X_5+0.29X_6+0.29X_7+0.29X_8+0.28X_9+0.26X_{10}+0.26X_{11}+0.26X_{12}$

$F_2=-0.15X_1+0.25X_2-0.19X_3-0.28X_4-0.23X_5+0.38X_6+0.19X_7-0.28X_8-0.30X_9-0.30X_{10}+0.46X_{11}+0.55X_{12}$

where X_1 to X_{12} represent the normalized values of each measured index.

The weight assigned to each principal component eigenvalue was determined by its proportion relative to the sum of all extracted eigenvalues, yielding a composite score formula of $F=0.89F_1+0.11F_2$. The ranking of treatments by composite score demonstrated the following sequence: M||V-PI2>M||V-PI3>M||V-PI1>M||V-RI2>M||V-RI1>SMI2>SMI1>M||V-RI3>SMI3 (Table 6). The treatment M||V-PI2 achieved the highest comprehensive score, demonstrating optimal performance among all evaluated treatments.

Affiliation function analysis Each eigenvalue magnitude represents the contribution rate of the ideal content variance, while each eigenvector indicates the contribution rate of individual indicators in the principal component analysis. The two principal components exhibited a cumulative variance contribution rate of 87.78%, indicating their capacity to substantially represent the measured indicators. The analysis and ranking of 12 indicators, including maize grain protein content, utilized the fuzzy affiliation function (Table 7). M||V-PI2 demonstrated the highest average affiliation function value, indicating superior comprehensive performance in terms of maize grain quality and yield compared to other treatments.

4. Discussion

4.1. Yield enhances advantage of intercropped with leguminous green manure and reduced irrigation quota

Crops demonstrate high sensitivity to water availability during their growth stages, with insufficient water supply during critical periods resulting in stunted growth and substantial yield reductions (Liu *et al.* 2017; Li H R *et al.* 2023). This research indicates that reduced irrigation decreases maize yield in monoculture systems. However, intercropping systems maintain yields comparable to conventional irrigation (400 mm) even with 15% deficit irrigation (Fig. 3). This maintenance of yield can be attributed to the asynchronous water sensitivity of crops in strip intercropping systems, which involves complex interactions, including competition for soil water and compensation mechanisms (Yin *et al.* 2020; Hou *et al.* 2024). In these systems, early-maturing crops may compete with late-maturing crops for water prior to harvest, as their root systems can infiltrate the root zone of the latter, particularly when late-maturing crops are less vigorous. However, higher soil moisture levels mitigate this competition intensity and facilitate adaptive changes in interspecies dynamics (Hou *et al.* 2024; Wang *et al.* 2024). Additionally, taller crops in intercropping systems reduce evapotranspiration losses by shading shorter crops, improve water infiltration, and enhance soil water content through abundant stems and leaves of green manure during the pre-birth period (Zhang Y *et al.* 2022; Wang *et al.* 2023; Li *et al.* 2025). After the harvest of early-maturing crops, late-

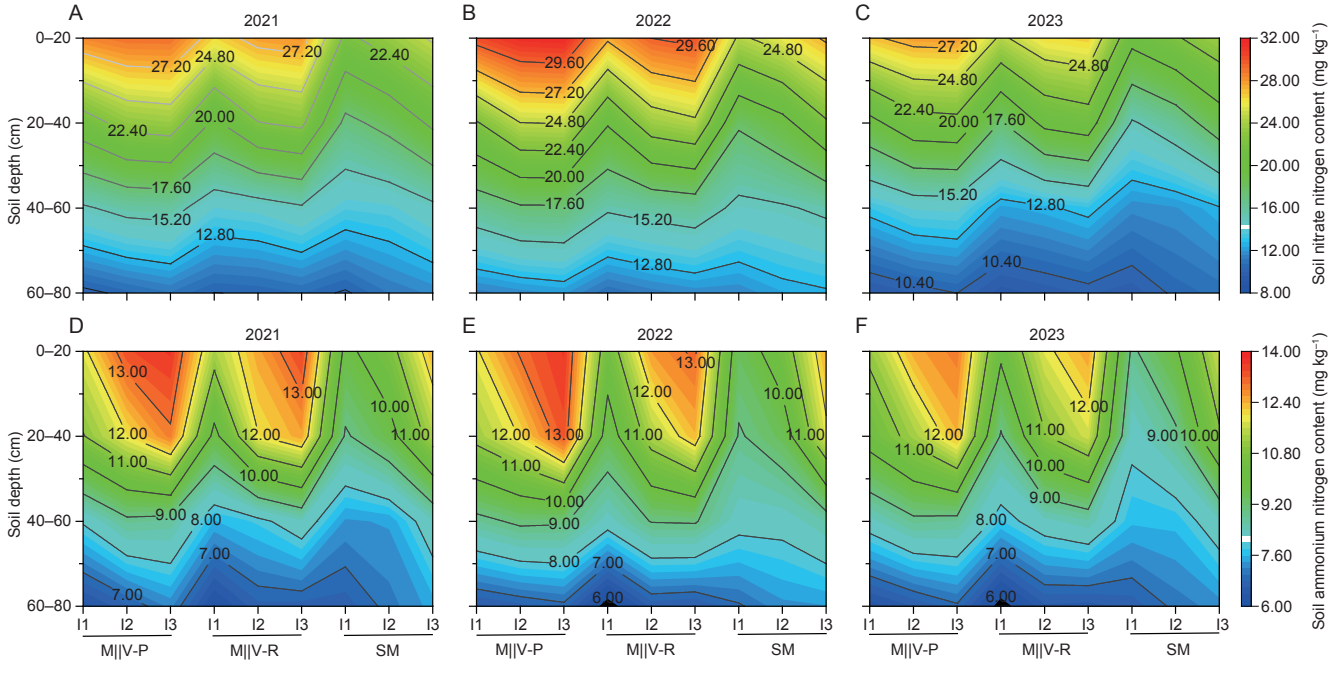


Fig. 5 Distribution of soil nitrate and ammonium nitrogen content in maize fields under varying cropping patterns and irrigation regimes. M||V-P, maize intercropping with leguminous green manure combined with full incorporation; M||V-R, maize intercropping with leguminous green manure combined with stubble retention; SM, maize sole cropping. I1, 280 mm (30% deficit irrigation); I2, 340 mm (15% deficit irrigation); I3, 400 mm (conventional irrigation).

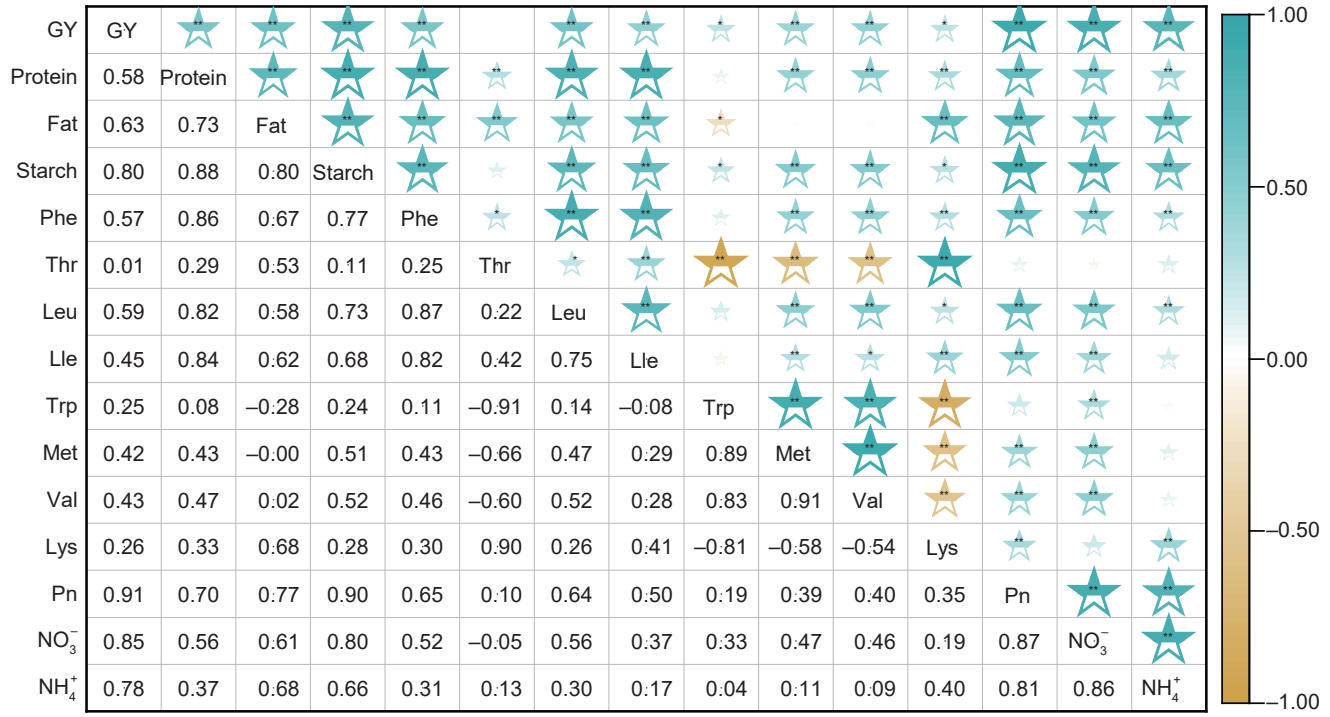


Fig. 6 The correlation analysis between maize grain yield (GY), kernel protein, fat, starch, essential amino acids, and net photosynthetic rate (Pn), NO_3^--N, and NH_4^+-N.

maturing crops utilize residual soil water in the vacated root zones (Yin *et al.* 2018; Hou *et al.* 2024). Moreover, returning crop residues to the field increases soil porosity, improves soil aggregate stability, and enhances water-holding capacity (Yin *et al.* 2018). These modifications create a more water-stable soil structure, ensuring adequate moisture for crop growth while reducing reliance on excessive irrigation and preventing yield losses (Mao *et al.* 2012). In rain-fed agricultural areas, green manure cultivation during drought years results in lower crop yields, though the impact remains minimal under normal or above-average rainfall conditions (Singh *et al.* 2023). In irrigated areas, adequate irrigation infrastructure ensures efficient production of integrated green manure intercropping systems, enhancing agricultural sustainability, while insufficient or poorly managed irrigation reduces intercropping system productivity (Jing *et al.* 2025; Li *et al.* 2025).

Numerous studies confirm that intercropping, particularly between grasses and leguminous plants, provides significant yield advantages compared to monoculture (Tilman 2020; Li *et al.* 2021; Luo *et al.* 2022; Li C J *et al.* 2023). These benefits primarily arise from the improved spatial arrangement of crops in intercropping systems, which enhances light interception and utilization, thereby increasing photosynthetic rates and promoting assimilated substance accumulation (Tilman 2020; Qiang *et al.* 2024). Additionally, grass crops promote nitrogen fixation by leguminous plants, which increases soil nutrient content and fertility, directly or indirectly supplying nitrogen to neighboring crops and enhancing overall crop yield (Hu *et al.* 2018; Zheng *et al.* 2022). The present study's findings align with previous research. Research conducted in the Hexi irrigation area comparing

Table 5 Principal component analysis of protein, fat, starch, Phe, Thr, Leu, Ile, Try, Met, Val, Lys levels, and grain yield across different treatments[1)]

Indicators	Payload		Indicators	Payload	
	PC1	PC2		PC1	PC2
X_1	0.96	–0.15	*X*9	0.87	–0.30
X_2	0.95	0.25	*X*10	0.81	–0.30
X_3	0.93	–0.19	*X*11	0.81	0.46
X_4	0.91	–0.28	*X*12	0.81	0.55
X_5	0.91	–0.23	Eigenvalues	9.35	1.20
X_6	0.88	0.38	Contribution rate (%)	77.87	10.02
X_7	0.87	0.19	Cumulative contribution rate (%)	77.87	87.89
X_8	0.87	–0.28			

[1)] X_1–X_{12} represent the concentrations of protein, fat, starch, Phe, Thr, Leu, Ile, Try, Met, Val, Lys, and grain yield, respectively.

Table 6 Principal component analysis and comprehensive evaluation of different treatments

Treatments[1)]	F_1	F_2	F	Ranking
M||V-PI1	2.63	0.08	2.35	3
M||V-PI2	2.88	0.19	2.58	1
M||V-PI3	2.64	0.28	2.38	2
M||V-RI1	2.00	–0.06	1.77	5
M||V-RI2	2.01	0.03	1.80	4
M||V-RI3	1.79	0.06	1.60	8
SMI1	0.81	–0.13	0.70	6
SMI2	0.74	–0.05	0.65	7
SMI3	0.52	0.06	0.47	9

[1)] M||V-P, maize intercropping with leguminous green manure combined with full incorporation; M||V-R, maize intercropping with leguminous green manure combined with stubble retention; SM, maize sole cropping.

Table 7 Affiliation function values of kernel quality and grain yield for each treatment

Treatments[1)]	Affiliation function value[2)]												Average affiliation function value	Ranking
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}		
M||V-PI1	0.95	0.57	0.78	0.85	0.81	0.79	0.78	0.60	0.88	0.81	0.66	0.58	0.754	3
M||V-PI2	0.88	0.77	0.92	0.84	0.81	0.79	0.77	0.79	0.87	0.81	0.77	0.91	0.829	1
M||V-PI3	0.79	0.91	0.95	0.72	0.71	0.63	0.67	0.65	0.73	0.61	0.78	0.95	0.759	2
M||V-RI1	0.58	0.35	0.38	0.68	0.66	0.71	0.64	0.49	0.72	0.72	0.51	0.46	0.576	5
M||V-RI2	0.51	0.44	0.46	0.62	0.59	0.65	0.59	0.59	0.61	0.66	0.57	0.70	0.582	4
M||V-RI3	0.43	0.49	0.48	0.49	0.51	0.55	0.44	0.55	0.47	0.46	0.65	0.70	0.518	6
SMI1	0.28	0.03	0.01	0.30	0.43	0.28	0.42	0.16	0.39	0.41	0.03	0.03	0.231	7
SMI2	0.13	0.13	0.07	0.22	0.36	0.16	0.32	0.23	0.30	0.23	0.23	0.21	0.215	8
SMI3	0.03	0.17	0.09	0.07	0.17	0.04	0.09	0.20	0.11	0.06	0.38	0.42	0.153	9

[1)] M||V-P, maize intercropping with leguminous green manure combined with full incorporation; M||V-R, maize intercropping with leguminous green manure combined with stubble retention; SM, maize sole cropping.
[2)] X_1–X_{12} represent protein, fat, starch, Phe, Thr, Leu, Ile, Try, Met, Val, Lys, and grain yield in sequential order.

different green manure incorporation methods revealed that plowing under whole-plant green manure provided greater yield benefits than returning only root stubble, attributing this difference to nutrient loss when only stubble was retained (Luo *et al.* 2022). In this study, intercropping systems with full green manure incorporation demonstrated higher maize yields than those with stubble retention, as evidenced by increased net photosynthetic rates (Fig. 4) and elevated nitrate-ammonium nitrogen content in the 0–40 cm soil layer (Fig. 5). A significant advantage of leguminous green manure lies in its ability to fix atmospheric N_2 into NH_4^+, providing nitrogen to both itself and adjacent crops, thereby reducing dependence on synthetic fertilizers (Lyu *et al.* 2023). However, excessive nitrogen fertilization suppresses biological nitrogen fixation, as legumes may preferentially uptake soil nitrogen rather than fixing atmospheric N_2 (Xia *et al.* 2023; Li *et al.* 2025). Therefore, optimizing nitrogen application rates is crucial for maximizing the benefits of legume-based intercropping systems in agricultural production.

Notably, 15% deficit irrigation maintained grain yields compared to conventional irrigation in intercropping systems, while achieving an 18.3% yield increase over conventional irrigation in monoculture. This significant improvement can be attributed to three key factors: 1) intercropping with green manure optimizes crop community structure, leading to enhanced resource utilization and reduced inter-plant competition, thereby increasing light energy capture by plant leaves and resulting in greater photosynthetic efficiency and overall productivity (Tilman 2020; Qiang *et al.* 2024); 2) the system facilitates increased soil inorganic nitrogen availability, enhancing nitrogen uptake during the maize plumping period and improving nutrient translocation to the grain (Yao *et al.* 2018; Xu *et al.* 2020); 3) green manure incorporation promotes water-stable aggregate formation, significantly improving soil water retention capacity and creating more favorable moisture conditions for crop growth (Fan *et al.* 2020; Liu *et al.* 2025).

4.2. The positive impact of intercropped leguminous green manure on maize kernel quality with reduced irrigation quota

In arid and semi-arid regions, water availability serves as a critical determinant of agricultural productivity, directly influencing both yield stability and grain quality (Alqudah *et al.* 2011). Research has established that declining soil moisture content adversely affects crop performance through multiple pathways: it increases yield vulnerability, reduces dry matter accumulation, and impairs the remobilization efficiency of essential nutrients (N, P, and K), collectively deteriorating grain quality parameters (Guo *et al.* 2023). Reduced irrigation results in decreased kernel starch content while increasing protein and free amino acid levels (Liu *et al.* 2013; De Santis *et al.* 2021; Yao *et al.* 2023). The present research demonstrated an increase in maize kernel protein content and kernel Phe, Thr, Leu, Ile, Val, and Met levels under reduced irrigation conditions. Conversely, starch, fat, and Lys contents showed a decreasing trend, consistent with previous finding (Liu *et al*. 2013). Environmental and genetic factors significantly influence crop grain quality, contributing to variations in maize grain nutrient composition. Light, temperature, and water play fundamental roles in maize growth, development, and grain formation (Shen *et al.* 2020a; Shen *et al.* 2020b). These factors regulate physiological processes governing nutrient transport and partitioning, thereby influencing the synthesis and accumulation of grain nutritional components (Li *et al.* 2020). This research demonstrated that intercropping leguminous green manure effectively enhances kernel quality parameters, increasing protein, starch, fat, and essential amino acid contents while maintaining a balanced amino acid profile (Tables 3 and 4). The starch synthesis pathway, which involves photosynthetic CO_2 fixation to produce sucrose followed by its conversion to starch precursors in developing grains, depends particularly on photosynthetic efficiency (Yue *et al.* 2022). The intercropping systems demonstrated superior photosynthetic performance (Fig. 3), especially during the maize R2 stage. The improved canopy architecture facilitated enhanced ventilation and light penetration compared to monoculture, resulting in greater carbohydrate production and subsequent starch accumulation in kernels (Gao *et al.* 2022). Nitrogen availability represents another crucial determinant of grain quality, particularly for protein synthesis (Kashiwagi 2021). Intercropping green manure significantly increased topsoil nitrate-ammonium nitrogen content (Fig. 5), demonstrating a synchronous increasing trend with protein and amino acids (Tables 3 and 4). This observation aligns with established

knowledge regarding leguminous nitrogen fixation; when integrated with gramineous crops, green manure provides direct and indirect nitrogen inputs. Following incorporation, green manure enhances soil enzyme activities (urease and alkaline phosphatase), boosts total and inorganic nitrogen pools, and ensures sustained nitrogen availability during late growth stages (Wang *et al.* 2017; Zhang *et al.* 2020). Studies have shown that both pre-anthesis carbon-nitrogen supply and their ratio coordination during grain filling critically regulate starch and protein biosynthesis in cereal grains (Zhou *et al.* 2004). Therefore, intercropping with leguminous green manure improves crop photosynthetic capacity and increases soil nutrient availability, promoting efficient source-to-sink nutrient translocation and accumulation in developing grains, achieving synergistic improvement in kernel nutritional quality (Feng *et al*. 2024). Additionally, utilizing low water-consumption crops in strip intercropping does not increase water usage (Anugroho *et al.* 2010); green manure incorporation enhances water storage capacity, ensuring adequate moisture for crop development under reduced irrigation regimes, which is essential for normal crop growth and development, and favors the formation of crop kernel quality (Daryanto *et al.* 2018).

This investigation focused specifically on elucidating how leguminous green manure intercropping influences grain quality through modifications in net photosynthetic rate and soil nitrate-nitrogen dynamics. However, the study did not examine the underlying physiological and biochemical mechanisms governing carbon and nitrogen metabolism, nor did it investigate the role of environmental variables in determining maize grain quality parameters. Future research should aim to comprehensively elucidate the optimization effects and mechanisms of intercropping green manure on maize grain quality, considering various aspects such as carbon and nitrogen metabolic pathways and environmental factors, particularly in water-limited conditions.

4.3. Comprehensive evaluation of intercropped leguminous green manure impacts on maize grain yield and quality with reduced irrigation quota

PCA is a statistical technique used to reduce multiple variables into a smaller set of comprehensive indicators that effectively represent the primary information of the original variables (Tang *et al.* 2021). Through the transformation of indicator coefficients into a range of [0,1], PCA facilitates more equitable comparison of metrics on a standardized scale compared to weighted scoring approaches (Zhang M X *et al.* 2022). In this research, PCA was applied to reduce 12 indicators from 9 treatments into 2 principal components, preserving 87.51% of the original information. This methodology enhances the comprehensive interpretation of the measured indicators. Significantly, 77.15% of the components demonstrated strong associations with protein and essential amino acids, including Phe, Thr, Leu, Ile, Try, and Met. These results highlight the importance of protein and essential amino acids as critical metrics for evaluating maize grain quality. Additionally, the 12 index parameters were analyzed by using reduced-dimension fuzzy mathematical membership function. The analysis indicated that the membership function values of M||V-P and M||V-R under I1, I2, and I3 all exceeded 0.50. Notably, M||V-PI2 exhibited the highest average affiliation function value, suggesting that this treatment could achieve optimal maize kernel quality and grain yield.

5. Conclusion

Under water-limited conditions, intercropping with green manure exhibits dual benefits of improving both maize productivity and kernel quality, with green manure full incorporation providing substantial advantages. Specifically, intercropping with leguminous green manure and 15% deficit irrigation maintains yield while preserving fat, starch, and Lys levels comparable to those obtained with conventional irrigation. Furthermore, this approach sustains high levels of protein and essential amino acids including Phe, Thr, Leu, Ile, and Met. These results arise from the intercropping system's enhancement of crop net photosynthesis rate and soil nitrate-ammonium nitrogen content, ensuring simultaneous improvement in maize yield and kernel quality. The evidence indicates that intercropping green manure with a full return strategy under 340 mm of irrigation represents an effective agronomic practice for achieving high-quality and efficient production in arid irrigation regions.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use AI in the preparation and writing of this manuscript.

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