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Multidimensional mechanisms of drip irrigation under plastic mulch in boosting maize yield in arid regions: Evidence from an eight-year fixed-site observation

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ABSTRACT

Achieving synergy between water conservation and yield increase remains a central challenge in arid agriculture. While drip irrigation under plastic mulch (DM) is known to outperform traditional border irrigation under plastic mulch (BM) in maize production, the systemic mechanisms behind this advantage lack comprehensive explanation through long-term observational data. This study addressed this gap via an eight-year (2014–2021) fixed-site comparative field experiment in northwest China. Results demonstrate that DM improved the field microclimate, increasing net radiation by 7.32% and soil water content by 21.60%. At the plant level, DM elevated the carbon-to-nitrogen ratio in roots, stems, and leaves, indicating enhanced indicating enhanced nitrogen use efficiency and stronger assimilate transport to grains. At the population level, DM boosted photosynthetic capacity, raising gross primary productivity and net ecosystem productivity by 13.05% and 15.58%, respectively. By regulating the "source-flow-sink" relationship, DM optimized the biomass partitioning pattern partitioning pattern, directing more photoassimilates towards grain filling. Structural equation modeling revealed that DM reconfigured the yield formation pathway and alleviated environmental stress limitations. Crucially, the leaf area index exerted the greatest total effect on fruit growth under DM—26.47% higher than under BM. Ultimately, the 12.85% yield increase under DM is attributed to the synergistic improvement of the field microenvironment, carbon-nitrogen metabolic efficiency, canopy photosynthesis, and biomass allocation, offering a scientific basis for reconciling water savings with yield gains in arid farmlands.

1. Introduction

Food security stands as a cornerstone of national stability, fundamentally underpinned by water security. Globally, arid and semi-arid regions cover approximately 45% of the Earth's terrestrial area (Berdugo et al., 2020). Irrigation, serving as a vital agricultural practice for securing grain production in drylands (Kang et al., 2017; Yang et al., 2018), consumes about 70% of freshwater worldwide (McDermid et al., 2023). Against this backdrop, China, possessing merely 6% of the world's freshwater resources, sustains 20% of the global population, thus facing the immense pressure between water availability and food production. Therefore, how to enhance grain yield under limited water and reinforcing the safeguard for food security poses a pressing and formidable challenge to us.

Fundamentally, the enhancement of crop yield originates from biomass accumulation and allocation. It involves complex biochemical and physical processes, including photosynthesis, respiration, nutrient translocation, and organic matter distribution, which are subject to multifactorial interactions (Gu et al., 2019; Lu et al., 2019). To be precise, leaves serve as the primary sites for photosynthesis, and a larger leaf area will augment photosynthetic activities, thus enabling greater biomass accumulation (Teixeira et al., 2014). Water limitation can suppress crop yield by impairing resource capture, specifically radiation interception and nitrogen uptake, and reducing conversion efficiencies,

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such as radiation use efficiency (Teixeira et al., 2014). Conversely, adequate water supply supports deeper rooting systems and expands absorption surfaces, thereby fostering the accumulation of above-ground biomass (Ma et al., 2025). Furthermore, beyond intrinsic genetic regulation (Su et al., 2018; Zhao et al., 2019), the allocation of biomass among organs is influenced by osmotic adjustment governing carbohydrate mobilization (Plaut et al., 2004). In addition, appropriate irrigation management can coordinate root-shoot growth, directing a greater proportion of photassimilates towards grain enrichment (Ma et al., 2025).

Maize ranks as one of the world's most crucial grain crops, holding strategic significance for national and regional food security. China is the second-largest maize producer globally, so further elevating the maize yield will be critical for stabilizing domestic and international grain markets (Luo et al., 2023). It has been well established that optimizing field management is capable of increasing overall maize yield by over 50% (Mueller et al., 2012). Conducting systematic field trials can provide empirical foundations for refining farmland water and nutrient management strategies (Ma et al., 2017; Coggins et al., 2025; Ren et al., 2025). Nevertheless, many current studies still lack long-term systematic observations and multidimensional datasets (Xu et al., 2015). This has substantially restricted the in-depth understanding of maize yield-enhancement mechanisms and hampered the advancement of precision agriculture frameworks.

To transit from 'experience-based farming' to 'precision agriculture', the integrated drip irrigation and fertigation technology, as an efficient and intensive field management approach, has been widely adopted across China. A meta-analysis focusing on Chinese studies indicated that, drip irrigation could increase crop yield by approximately 12% over the traditional practices (Li et al., 2021). When 100%-120% of the conventional drip irrigation volume, the yield enhancement could even surpass that of border irrigation by 14.55% (Yang et al., 2023b). Particularly, the application of drip irrigation under plastic mulch (DM) in arid regions of China has demonstrated a greater yield-increasing potential than traditional border irrigation under plastic mulch (BM) (Guo and Wu, 2024; Qi et al., 2024).

Although DM has been demonstrated to significantly enhance maize yield compared to traditional BM, a comprehensive and systematic explanation of its underlying mechanisms based on long-term, fixed-site observational data remains lacking. Accordingly, we conducted an eight-year, fixed-site field experiment in a typical arid region of Northwest China. The specific objectives were as follows: (1) to systematically analyze the differences in environmental characteristics, carbon flux dynamics, and patterns of biomass accumulation and allocation between the DM and BM systems; and (2) to elucidate the mechanisms underlying the maize yield increase under DM compared to BM from multiple perspectives and to quantify the regulatory pathways governing yield formation. Through this research, we aim to provide solid theoretical and practical support for synergizing sustainable agricultural water use and safeguarding food security in arid regions.

2. Materials and methods

2.1. Experimental site description

The long-term field experiment was performed at the National Field Scientific Observation and Research Station on Efficient Water Use of Oasis Agriculture (37°52'N, 102°50'E, 1581 m) in Wuwei City, Gansu Province, Northwest China. The site has a temperate continental climate characterized by intense solar radiation, abundant sunshine, and a relatively short frost-free period. An automatic weather station (AWS) (Hobo, Onset Computer Corp, USA) was installed to continuously monitor and record meteorological data. The mean values and standard deviations (STDEV) of atmospheric pressure (Pa), solar radiation (Rs), air temperature (Ta), relative humidity (RH), precipitation (P), and wind speed (Ws) during the experimental period (2014–2021) are presented in Table 1.

Both maize fields were covered with transparent plastic mulch, which was thickness of 8 μm, and shortwave transmittance, reflectance, and absorptance of 0.85, 0.10, and 0.05, respectively. The DM adopted a high-frequency, low-volume approach, with an irrigation frequency approximately twice that of BM, while reducing water usage and nitrogen application by 13% and 19%, respectively. Irrigation and nitrogen application of maize fields under DM and BM from 2014 to 2021 are presented in Appendix 1. For more detailed information on irrigation and precipitation, please refer to Appendix 2. All agricultural activities—such as film laying, hole punching, sowing, and harvesting were carried out with machinery.

Samples were taken from the soil before sowing at a depth of 0–100 cm in the maize field. The surface soil was divided into layers of 10 cm each, and the remaining soil layers were divided into layers of 20 cm each. The dry bulk density of the soil was measured using the ring tool method, the organic carbon of the soil was determined using the potassium dichromate external heating method, and the total carbon content and total nitrogen content of the soil were measured using the elemental analyzer (Vario Pyro Cube analyzer, Elementar, Germany). The mean dry bulk density, soil organic carbon content, and C/N at a depth of 0–100 cm were 1.54 g cm^{-3}, 6.54 mg g^{-1}, and 27.80% under DM, and 1.52 g cm^{-3}, 4.08 mg g^{-1}, and 32.27% under BM. More detailed physical properties data can be found in Appendix 3.

2.2. Experimental measurements and basic data

2.2.1. Measurement of environmental factors and carbon flux

An eddy covariance (EC) system was installed at the center of each maize field, enabling continuous monitoring of environmental factors such as net radiation (Rn), canopy temperature (Tc), vapor pressure deficit (VPD), soil water content (SWC), and soil temperature (Ts). It sampled at a frequency of 10 Hz and output data at 30-minute intervals. The EC system was equipped with a radiation sensor (CNR4, Kipp & Zonen, Netherlands), which can directly measure the upward long-wave radiation (ULR) and upward short-wave radiation (USR), as well as downward long-wave radiation (DLR) and downward short-wave radiation (DSR) above the canopy. The value of Rn is equal to the difference between downward radiation (DSR + DLR) and upward radiation (USR + ULR).

The SWC at depths of 20 cm, 40 cm, 60 cm, 80 cm, and 100 cm was measured with a CS616 probe (Campbell Scientific, Inc., USA), and the Ts at depths of 20 cm, 40 cm, 60 cm, and 80 cm using 109 L temperature probes (Campbell Scientific, Inc., USA). In this study, SWC and Ts represent mean values across the measured soil depths. In order to make the data of SWC more representative, this study also adopted the traditional drilling soil sampling method to collect soil samples from the exposed soil and the soil under the mulch in the farmland. The soil sampling depth corresponded to the observation depth of the CS616 probe. The sampling frequency was 7 days, and measurements were also

Table 1
Values of main meteorological factors in the experimental area from 2014 to 2021.

Year	Pa (Kpa)	Rs (W m^{-2})	Ta (°C)	RH (%)	P (mm)	Ws (m s^{-1})
2014	84.09	169.02	8.82	53.46	276.84	0.51
2015	84.09	171.39	9.30	54.14	192.85	0.58
2016	84.05	171.91	9.89	51.76	160.14	0.67
2017	84.14	170.90	9.36	50.75	183.23	0.65
2018	84.08	167.80	8.76	53.07	220.34	0.51
2019	84.08	175.44	9.10	54.64	157.76	0.46
2020	84.10	180.45	9.05	51.47	151.80	0.59
2021	84.09	177.87	9.66	50.67	202.80	0.65
Mean	**84.09**	**173.10**	**9.24**	**52.49**	**193.22**	**0.58**
STDEV	**0.03**	**4.12**	**0.37**	**1.44**	**38.71**	**0.07**

conducted before and after irrigation and after precipitation. The moisture content of the collected soil samples was determined by the drying method, and a functional relationship was established between the moisture content of the soil determined by the soil sampling drying method and the corresponding instrument observation data to correct the SWC throughout the entire growth period of maize.

The net ecosystem exchange (NEE) in maize fields can be directly obtained with the EC system, and the net ecosystem productivity (NEP) can be derived from NEE. Gross primary productivity (GPP) is the sum of ecosystem respiration (ER) and NEP. At night, maize assimilates zero CO_2, meaning GPP is zero. Nighttime ER, which equals to nighttime NEE, is used to fit the Van't Hoff model (Collatz et al., 1991) for estimating daytime ER. Daytime GPP is then obtained by adding daytime NEP and daytime ER.

2.2.2. *Measurement of biotic factors*

Throughout the entire growth period of maize, eight representative plants were selected every 7–10 days for the following purposes: (I) The length and width of each leaf were measured using a ruler, to calculate leaf area index (LAI). (II) They were separated into roots, stems, leaves, and fruits, and then dried until constant weight was achieved, to determine their respective biomass. (III) Determination of organic carbon content. The dried plant samples from the same sampling date and under the same management methods were grouped by organ (roots, stems, leaves, and fruits). Each organ group was finely ground, passed through a 0.25 mm sieve and thoroughly homogenized. Approximately 0.01 g of the homogenized sample was weighed and 5 ml of potassium dichromate solution and 5 ml of concentrated sulfuric acid were added. The mixture was digested in an oil bath and the remaining chromic acid was titrated with 0.2 mol L ferrous sulfate solution. The organic carbon content was calculated based on the consumption of chromic acid. Each organ sample was tested in triplicate and a blank control was set up to ensure the accuracy of the analysis. (IV) Determination of total carbon, total nitrogen, and carbon-to-nitrogen ratio (C/N). For total carbon and nitrogen analysis, the same set of homogenized, ground samples (as prepared in step III) were used. Approximately 0.01 g of sample per organ was weighed for analysis. Total carbon and total nitrogen contents were determined using a Vario Pyro Cube elemental analyzer (Elementar, Germany). The analyzer was calibrated using certified reference materials (acetanilide) prior to sample runs. The C/N was calculated directly from the obtained total carbon and total nitrogen contents. For each management methods and sampling date, every plant organ was analyzed in triplicate. The carbon and nitrogen contents in different maize organs under DM and BM in 2021 were shown in Fig. 1.

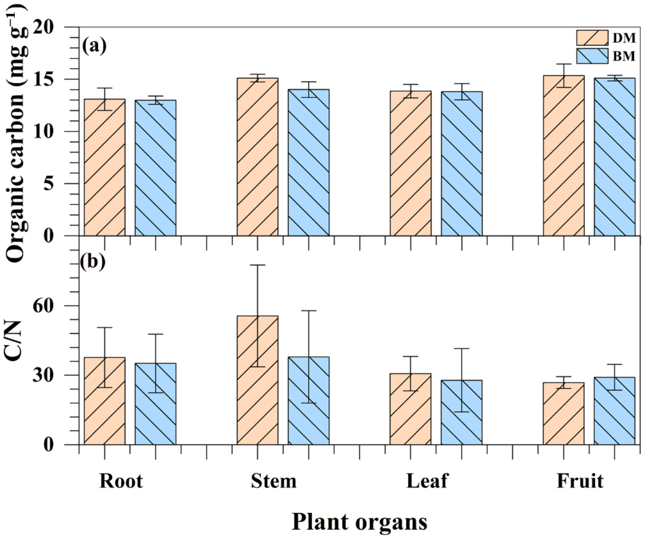

Fig. 1. The organic carbon content and C/N in various organs of maize plants under DM and BM.

In this study, the measured LAI and biomass values were processed using linear fitting with a moving window of four measured points, which advances two points each time, to obtain daily-scale data of biotic factors. To eliminate marginal effects and accurately obtain harvest indicators such as maize yield, random sampling was introduced during the harvest stage. In each experimental plot, three quadrats with uniform growth conditions were selected. From the center of each quadrat, ten maize plants were randomly selected for yield determination. Measurements included the biomass of plant organs, number of kernel rows per ear, number of kernels per row, grain weight per ear (g), and hundred-kernel weight (g). They were used to determine maize yield, kernel rate (ratio of grain weight to cob-included ear weight), and harvest index (ratio of grain weight to aboveground biomass).

2.3. *Statistical analysis*

Structural equation modeling (SEM) was introduced to quantify the extent to which latent variables influence observed ones, as well as the interrelationships among latent variables. Its construction and computation employed SPSS 21.0 (SPSS, Chicago, Illinois, USA) and AMOS software (IBM SPSS Amos 22.0). Its network in the SEM was developed based on existing knowledge, and only paths with significant effects were retained. With reference to Wang et al. (2023b), a model having met the following criteria was considered satisfactory: Adjusted Goodness of Fit Index (AGFI) > 0.90, Tuck-Lewis Index (TLI) > 0.90, and Comparative Fit Index (CFI) > 0.95.

The daily-scale SWC, Rn, VPD, Tc, and LAI were selected as driver variables in the SEM based on their fundamental and direct roles in controlling crop growth and yield formation. SWC determines plant water availability, directly affecting stomatal conductance, photosynthesis, and turgor-driven cell expansion. Rn is the primary energy source for photosynthesis. VPD and Tc are key indicators of canopy-level evaporative demand and plant water status, jointly influencing stomatal behavior and transpiration. LAI integrates canopy development and directly determines light interception capacity. These variables collectively represent the principal environmental (SWC, Rn, VPD, Tc) and biological (LAI) constraints on daily carbon gain and assimilate partitioning, making them theoretically appropriate for modeling the pathway to fruit growth.

3. Results

3.1. *Dynamic changes of environmental and biological parameters*

Fig. 2 shows the interannual mean dynamics of Rn, Ta, RH, VPD, SWC, Ts, and LAI in maize fields under DM and BM from 2014 to 2021, plotted against days after sowing. They generally showed consistent overall trends under both irrigation methods. Notably, due to differences in irrigation frequency and volume, the fluctuations in SWC during the growing season differed significantly between DM and BM. Specifically, the multi-year means for Rn, Ta, RH, VPD, SWC, Ts, and LAI under DM were 139.22 $W\ m^{-2}$, 19.27 °C, 41.80%, 1.43 kPa, 0.31 $cm^3\ cm^{-3}$, 18.76 °C, and 3.11 $m^2\ m^{-2}$, respectively, while under BM, they were 129.73 $W\ m^{-2}$, 18.83 °C, 40.07%, 1.42 kPa, 0.26 $cm^3\ cm^{-3}$, 18.29 °C, and 2.80 $m^2\ m^{-2}$, respectively. Although the multi-year mean values of VPD were similar between the two irrigation methods, they were more stable under DM. The standard deviation of VPD under DM was 0.16 kPa, compared to 0.20 kPa under BM.

3.2. *Dynamic changes of carbon flux*

The dynamic changes of GPP and NEP under DM and BM were shown in Fig. 3. Both exhibited a unimodal dynamic pattern—initially increasing and then decreasing—throughout the entire maize growing

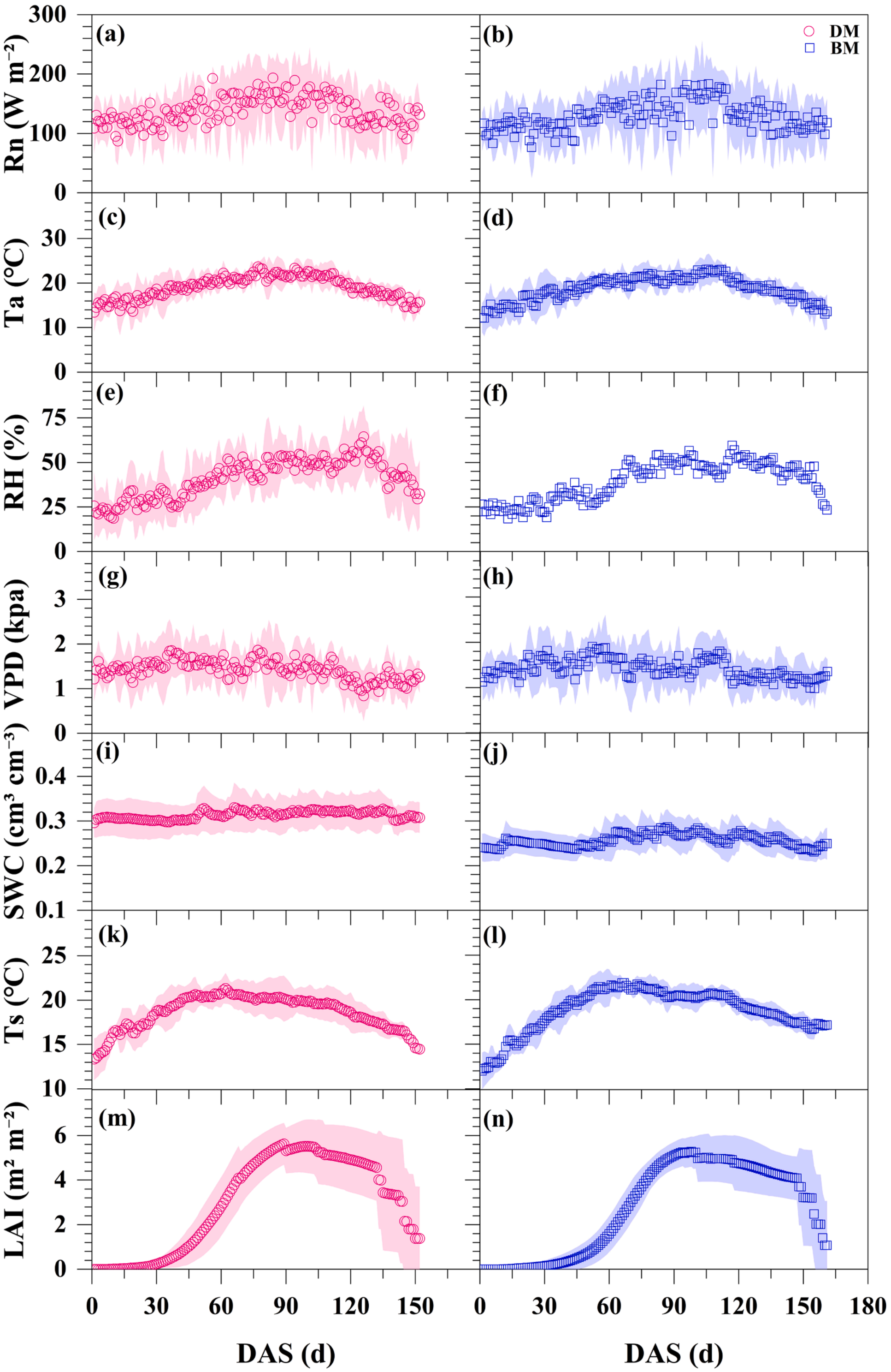

Fig. 2. Dynamics of multi-year mean values of various parameters in maize fields under DM and BM over days after sowing (DAS). (a) and (b) show the variation of net radiation (Rn) with DAS, (c) and (d) show the variation of air temperature (Ta) with DAS, (e) and (f) show the variation of relative humidity (RH) with DAS, (g) and (h) show the variation of vapor pressure deficit (VPD) with DAS, (i) and (j) show the variation of soil water content (SWC) with DAS, (k) and (l) show the variation of soil temperature (Ts) with DAS, and (m) and (n) show the variation of leaf area index (LAI) with DAS. *Note: The colored shading represents the range of multi-year standard deviation for each parameter. Red and blue represent the data for maize fields with drip irrigation under plastic mulch (DM) and maize fields with border irrigation under plastic mulch (BM).*

period. Except during the early growth stage and the senescence stage after maturity, NEP remained positive for most of the growth period. From 2016–2021, the multi-year GPP and NEE under DM were 11.83 g $C\cdot m^{-2}\cdot d^{-1}$ and –5.56 g $C\cdot m^{-2}\cdot d^{-1}$, respectively, while under BM, they were 10.73 g $C\cdot m^{-2}\cdot d^{-1}$ and –5.07 g $C\cdot m^{-2}\cdot d^{-1}$, respectively. Compared with BM, DM increased the cumulative GPP and NEP over the entire growth period by 3.58% and 3.11%, respectively, indicating that DM could enhance both the plant carbon assimilation capacity and the ecosystem carbon sink ability.

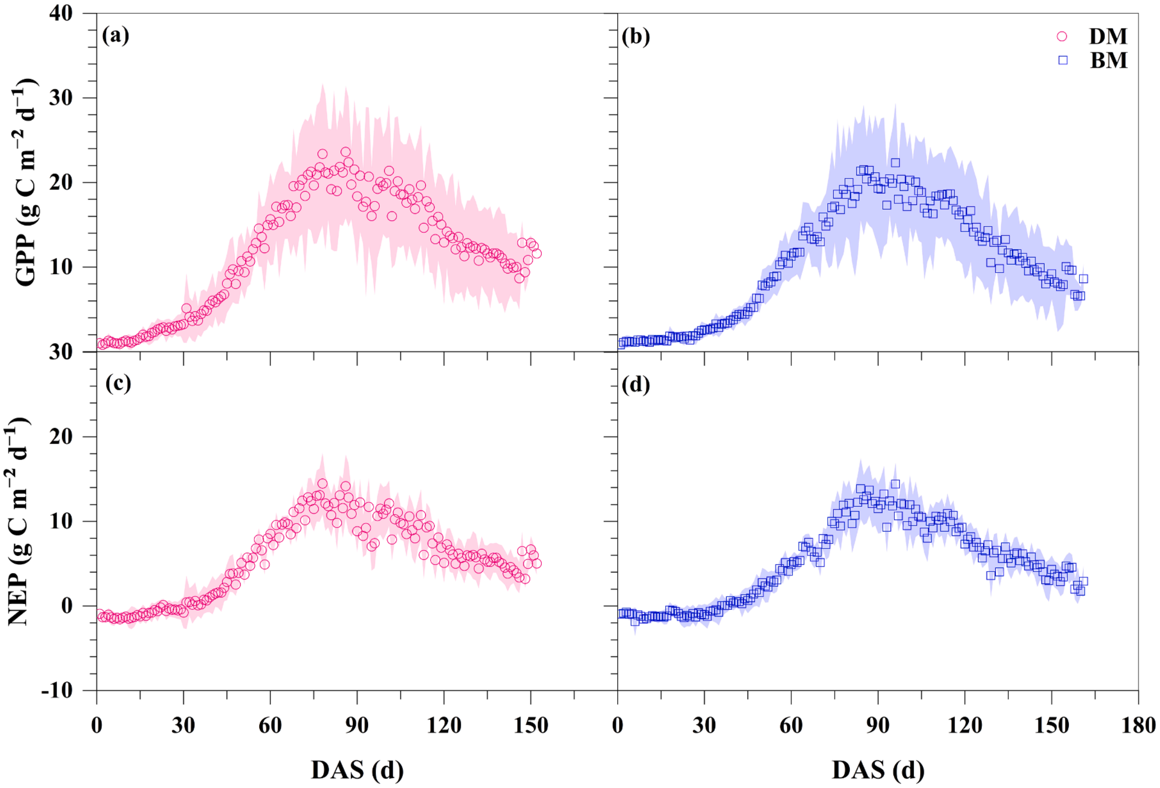

Fig. 3. Dynamics of multi-year mean values of gross primary productivity (GPP) and net ecosystem productivity (NEP) in maize fields under DM and BM over days after sowing (DAS). (a) and (b) show the variation of GPP with DAS, and (c) and (d) show the variation of NEP with DAS. *Note: Since the carbon flux was observed under the BM method since 2016, the data in the figure represent the mean values and standard deviations under drip irrigation under plastic mulch (DM) and border irrigation under plastic mulch (BM) for the period from 2016 to 2021. Red and blue represent the data for maize fields with DM and BM.*

3.3. *Allocation of maize biomass*

The biomass allocation among different organs of maize during the vegetative growth and reproductive growth stages under the two irrigation practices was shown in Fig. 4. During the vegetative growth stage, the root biomass allocation ratio under BM was 9.09% higher than

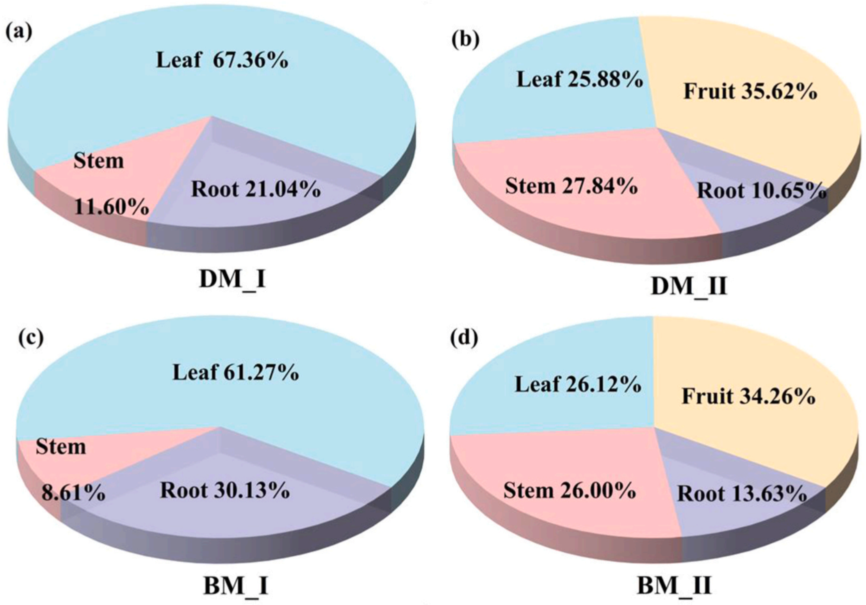

Fig. 4. Distribution of biomass in different organs of maize under DM and BM methods during the vegetative growth stage (I) and the reproductive growth stage (II). (a) represents the allocation ratio of root, stem and leaf biomass to the total biomass of maize in the vegetative growth stage under DM. (b) represents the allocation ratio of root, stem, leaf and fruit biomass to the total biomass of maize in the reproductive growth stage under BM. (c) represents the allocation ratio of root, stem and leaf biomass to the total biomass of maize in the vegetative growth stage under DM. (d) represents the allocation ratio of root, stem, leaf and fruit biomass to the total biomass of maize in the reproductive growth stage under BM.

that under DM, while the leaf and stem allocation ratios were 6.09% and 2.99% lower, respectively. In the reproductive growth stage, the fruit biomass proportion was the highest under both irrigation methods, though it was 1.36% lower under BM than under DM. Meanwhile, the root biomass allocation ratio under BM remained 2.98% higher than that under DM.

Maize organs compete for photosynthetic products during growth. The correlations between biomass allocation ratios of different organs were illustrated in Fig. 5. During both growth stages, the direction of correlations (positive or negative) among organ allocation ratios was consistent between DM and BM. However, all correlations were significant under DM, whereas under BM, the correlations between leaf and stem allocation ratios during the vegetative growth stage and between root and stem allocation ratios during the reproductive growth stage were not significant. Under both irrigation methods, the strongest correlation was observed between leaf and fruit biomass allocation ratios, with the coefficient of –0.90 and –0.94 for DM and BM, respectively.

3.4. Yield and its regulatory pathways

The biomass, kernel rate, and harvest index of maize at harvest under DM and BM were shown in Table 2. In 2017, rust disease broke out in the maize fields, and the maize leaves showed obvious lesions with a high density. The distribution of rust disease on the leaves of some plants had reached over 25%. The severity of the disease in maize fields under DM was higher than those under BM. Except for 2017, when disease outbreak under DM resulted in lower grain weight, aboveground biomass, and total biomass than those under BM, DM performed better across all other years. Statistical results from 2014 to 2021 show that the multi-year mean grain weight, total biomass, kernel rate, and harvest index under DM were 12.85%, 6.48%, 9.54%, and 5.47% higher than those under BM, respectively.

We employed SEM to quantitatively trace how the key environmental and growth factors identified the daily increment of maize fruits (net fruit). Daily-scale SWC, Rn, VPD, Tc, and LAI served as driving variables, while the net fruit was designated as the target variable (Fig. 6). The direct and indirect effects of each factor on maize net fruit were summarized in Table 3. Under the DM method, Rn, VPD, and Tc did not exert direct effects on net fruit but indirectly influenced net fruit acting on LAI. Under the DM method, only LAI and SWC directly affected net fruit, whereas under the BM method, SWC was the sole factor having an indirect effect. The total effects of all factors on net fruit under the DM method in a descending order were LAI > SWC > Tc > Rn > VPD, while Conversely, under the BM method, the order was LAI > VPD > Tc > SWC > Rn. Notably, LAI exhibited the largest total effect on net fruit under both irrigation methods, with standardized total effect values of 0.43 and 0.34, respectively.

4. Discussion

4.1. Yield-increasing mechanisms of maize under DM compared with BM

Based on the aforementioned empirical findings, this study posits that the yield increase achieved by DM (compared to BM) in maize fields of arid Northwest China was not attributable to a single factor, but rather results from the synergistic effects of a series of interconnected

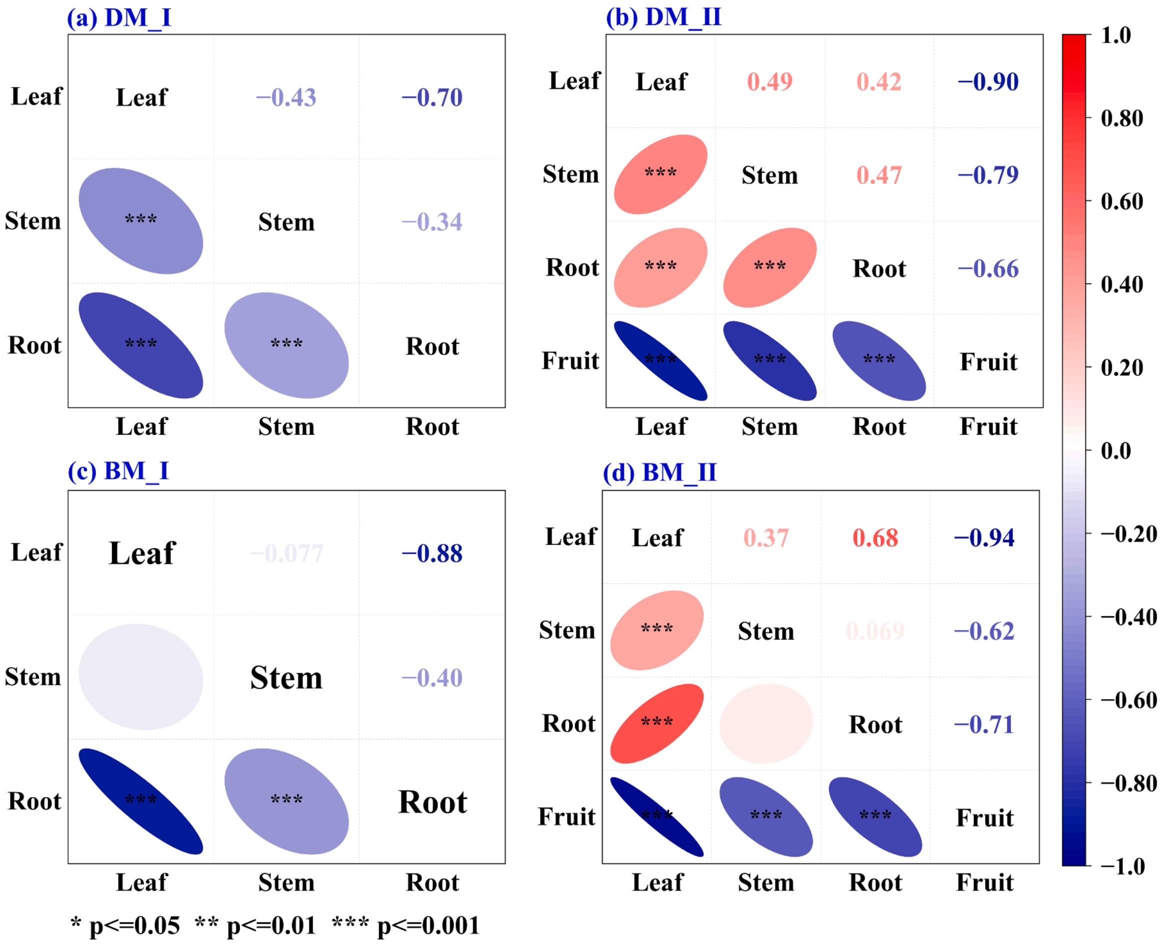

Fig. 5. Correlation among biomass allocation ratios of different maize organs under DM and BM methods during the vegetative growth stage (I) and the reproductive growth stage (II).

Table 2
Biomass, kernel rate and harvest index of maize at harvest under DM and BM.

Year	Irrigation methods	Grain weight (kg ha^{-1})	Aboveground biomass (kg ha^{-1})	Total biomass (kg ha^{-1})	Kernel rate (%)	Harvest index
2014	DM	9040.00	20949.30	23249.45	68.85	43.15
	BM	6900.00	16221.60	16269.40	45.99	42.54
2015	DM	9970.00	25610.60	28969.44	67.47	38.93
	BM	8520.00	19685.60	22976.50	69.32	43.28
2016	DM	10950.00	26289.40	29303.92	79.86	41.65
	BM	10440.00	25071.60	28192.20	78.01	41.64
2017	DM	5290.00	14357.29	15595.94	70.62	36.85
	BM	6760.00	20603.50	22277.70	53.31	32.81
2018	DM	7920.00	20344.33	21957.05	59.36	38.93
	BM	7530.00	18641.50	20834.50	59.88	40.39
2019	DM	16552.30	35564.54	37953.90	82.74	46.54
	BM	13405.07	31984.92	34150.00	79.39	41.91
2020	DM	17291.16	31611.47	32722.19	80.65	54.70
	BM	14749.26	30334.19	32123.88	76.29	48.62
2021	DM	16617.48	31018.58	32304.56	83.99	53.57
	BM	14662.32	29718.73	31713.37	81.90	49.34
2014–2021	**DM**	**11703.87**	**25718.19**	**27757.06**	**75.70**	**45.51**
	BM	**10370.83**	**24032.71**	**26067.19**	**69.11**	**43.15**

physical, physiological, and ecological processes. The underlying yield-increasing mechanisms can be systematically attributed to the following interrelated aspects:

4.1.1. *Improved field microclimate*

Compared with BM, DM systematically improved the microclimate in the maize field (Wang et al., 2023a). Plant growth adjusts its growth and development trajectory according to environmental factors (Puglielli et al., 2021). A favorable growth environment is the foundation for achieving efficient growth and increased grain yield (Liu et al., 2018; Deng et al., 2025). In this study, the multi-year mean values of Rn, Ta, RH, VPD, SWC, and Ts under DM were superior to those under BM. Among them, Rn and SWC were particularly prominent, with rises of 7.32% and 21.60%, respectively. The frequent soil wet-dry alternation caused by drip irrigation and changes in vegetation coverage due to crop growth, led to different underlying surface conditions from BM, thereby altering the characteristics of surface energy reflection (Yang et al., 2023a; Lin et al., 2025). The drip irrigation system achieved highly efficient utilization of water resources, significantly reducing water loss caused by deep seepage and ineffective evaporation (Flores et al., 2021; Wang et al., 2021). Thus, the maize field under drip irrigation had higher SWC (Qin et al., 2016). Existing research confirms that SWC is a key environmental factor affecting crop yield, especially in arid regions where its influence is more pronounced (Madias et al., 2025).

4.1.2. *Enhanced carbon-nitrogen metabolic efficiency*

Plant growth and development heavily rely on the coordinated interactions between the carbon metabolism and the nitrogen metabolism (Nunes-Nesi et al., 2010). Indeed, what truly regulates crop growth is the balanced interplay of both elements, rather than carbon or nitrogen alone (Martin et al., 2002). The C/N within plant tissues serves as a pivotal metric for evaluating the harmony of C–N metabolism and the allocation strategy of photoassimilates (Liu et al., 2025). Typically, a relatively high C/N suggests enhanced nitrogen utilization efficiency (Zhang et al., 2020). Agronomic management measures profoundly affect the contents and proportions of carbon and nitrogen in crops (Ma et al., 2019). This study revealed that under DM, the C/N in the root, stem, and leaf organs was higher than that under BM. This implies that DM helps improve nitrogen usage efficacy in maize and facilitates the preferential flow of photoassimilates into yield-forming sinks. Especially in stems, the C/N under DM was 46.61% higher than that under BM.

This phenomenon offers a physiological-level rationale explaining how DM more efficiently promotes the direction of biomass accumulation toward grain yield formation. Photosynthetic nitrogen-use efficiency represents another essential index measuring the effectiveness of nitrogen deployment during photosynthesis (Qiang et al., 2023), and exhibits a significant positive correlation with kernel output (Wang et al., 2024). Prior investigations have further verified that photosynthetic nitrogen-use efficiency under DM was markedly higher than that under BM (Zhao et al., 2025), hence partly driving higher maize productivity in this system.

4.1.3. *Increased population photosynthetic capacity*

This study demonstrated that GPP and NEP in maize fields under DM were 13.05% and 15.58% higher than those under BM, respectively. This finding reflects not only enhanced photosynthetic capacity of the maize canopy under DM but also established a material basis for biomass accumulation. Increased biomass has been recognized to be vital in achieving high yields (Li et al., 2023). In particular, maize yield is closely associated with photosynthetic performance during the late reproductive stage (Wang et al., 2024), as approximately 90% of grain assimilates are synthesized after flowering (Gao et al., 2017). In our study, maize under DM maintained higher photosynthetic functionality during later growth stages, ensuring sufficient supply of photoassimilates required for grain filling and constituting a decisive carbon source underpinning high yield. Moreover, the multi-year mean LAI under DM surpassed that under BM by 11.05%, expected to enhance the interception of photosynthetically active radiation and consequently raise the overall photosynthetic rate (Guo et al., 2024).

4.1.4. *Optimized biomass partitioning pattern*

This study has confirmed that DM can systematically optimize the biomass allocation pattern in maize. As illustrated in Fig. 4, DM significantly reduced both the root-to-stem and the root-to-leaf ratios across vegetative and reproductive growth stages, while promoting the proportion of photoassimilates allocated aboveground. Based on the source–sink relationship theory, the allocation of photosynthetic products is regulated by the supply capacity of source organs, the competitiveness of sink organs, and the transport capacity of the phloem (Lacointe, 2000). Compared with BM, DM increased the leaf (the primary "source" organ) allocation ratio by 5.09% during the vegetative growth stage, establishing a foundation for efficient photosynthesis. During the reproductive growth stage, the root allocation ratio decreased by 2.98% under DM, facilitating more resources toward yield formation in the aboveground parts. Throughout both maize growth stages, the stem (the main "flow" organ) allocation ratio under DM remained higher than that under BM, thereby enhancing the plant's capacity for transporting water and nutrients and ensuring effective translocation of photoassimilates to sink organs.

This reallocation mode has strengthened the photosynthetic "source",

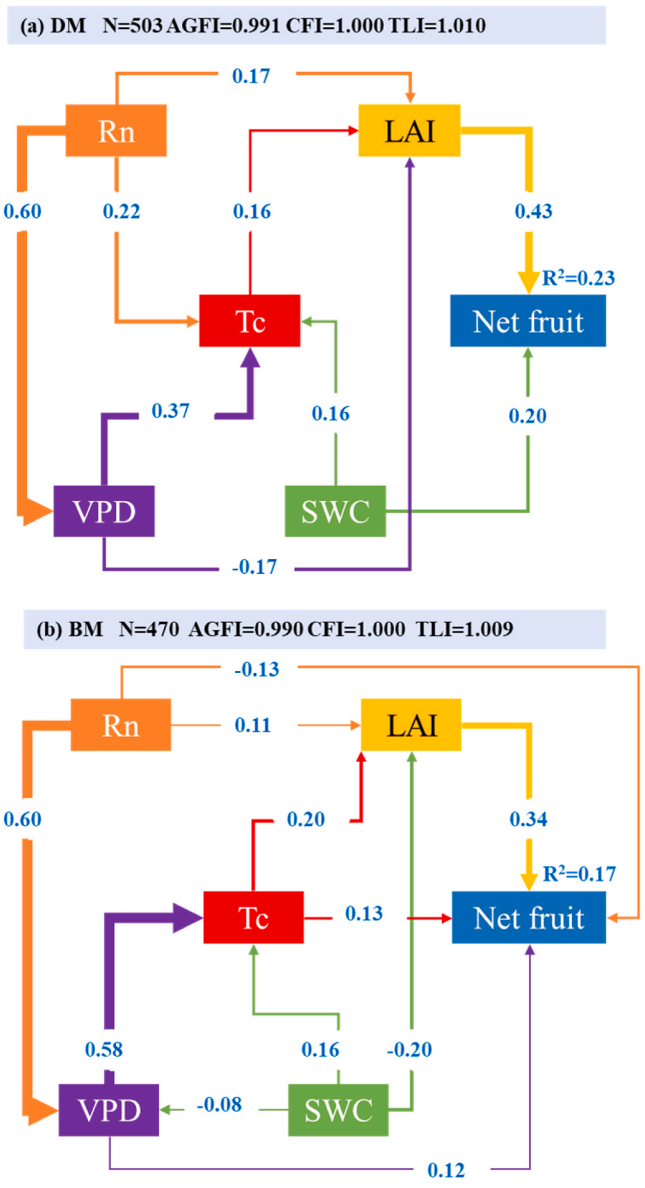

Fig. 6. The regulatory pathways of daily increment of maize fruits (Net fruit) under DM and BM. *Note: Rn: net radiation, Tc: canopy temperature, VPD: vapor pressure deficit, SWC: soil water content, and LAI: leaf area index. Solid lines in the figure represent significant paths in the structural equation model (SEM). The numerical values on the single-arrow paths indicate the direct influence of the tail factor on the head factor, while the product of the values along continuous single arrows represents the indirect influence. The width of the lines reflects the degree of influence. The R^2 value beside the response variable represents the variance that different influencing factors and their constructed relationships can explain. N denotes the number of sample groups included in the SEM. The adjusted goodness-of-fit index (AGFI), comparative fit index (CFI), and Tucker-Lewis index (TLI) are important evaluation indicators for proving the rationality of the SEM.*

facilitated the transport pathway, and reduced unnecessary root consumption, thereby enabling more efficient delivery of photoassimilates to the sink (grain). The optimization of this "source-flow-sink" continuum under DM is underpinned by improved physiological conditions. Specifically, the stable and favorable soil moisture maintained by high-frequency drip irrigation enhances phloem loading and transport capacity (the "flow"), while likely modulating root-sourced hormonal signals (e.g., reduced abscisic acid, enhanced cytokinins) that strengthen sink demand and assimilate partitioning towards grains.

Table 3
Direct and indirect effects of environmental factors on net fruit under DM and BM.

Irrigation methods	Effects	SWC	Rn	VPD	Tc	LAI
DM	Direct	0.20				0.43
	Indirect	0.01	0.06	–0.05	0.07	
	Total	0.21	0.06	–0.05	0.07	0.43
BM	Direct		–0.13	0.12	0.13	0.34
	Indirect	–0.06	0.18	0.11	0.07	
	Total	–0.06	0.05	0.23	0.20	0.34

Note: SWC: soil water content, Rn: net radiation, VPD: vapor pressure deficit, Tc: canopy temperature, and LAI: leaf area index. The direct effect represents the immediate impact of a factor on net fruit, while the indirect effect reflects the cumulative influence mediated by other variables in the model. The total effect is the sum of direct and indirect effects, indicating the overall contribution of a factor to net fruit.

Further analysis indicated that maize yield levels were closely associated with the allocation and transfer ratios of biomass among different organs (Zhang et al., 2022). This study reveals that the correlations among biomass allocation ratios of various organs differ between the two irrigation methods (Fig. 5). Precisely, under BM, the connections between biomass allocation ratios of different organs were relatively weak. In contrast, DM led to a more coordinated and efficient supply–demand relationship between source organs (leaves, stems) and sink organs (fruit). Correlation results show that under both irrigation methods, the fruit biomass allocation ratio displays significant negative correlations with the biomass allocation ratios of leaves, stems, and roots. In particular, the leaf biomass allocation ratio exhibits the strongest negative correlation with the fruit biomass allocation ratio, indicating that the contribution of leaf biomass remobilization to fruit biomass is the greatest during this stage.

4.1.5. Altered yield formation pathway

SEM analysis revealed fundamental differences in the regulatory pathways of yield formation between DM and BM (Fig. 6). LAI can largely reflect the strength of a plant's photosynthetic capacity. Previous research has generally indicated a positive correlation between LAI and crop yield (Liu et al., 2021). In this study, LAI exhibited a significantly stronger direct positive effect on net fruit under DM (0.43) than under BM (0.34), serving as the most critical positive predictor variable in yield formation. The total effect of LAI on the net fruit under DM was 26.47% higher than that under BM. Moreover, the mean LAI under DM was 11.05% higher than that under BM, indicating its decisive advantage in yield formation. SWC also has a significant direct effect (0.20) and a relatively weak indirect effect (0.01) on net fruit under DM, suggesting that DM can maintain stable soil moisture, directly supporting the absorption of water and nutrients by roots, while BM exhibited no direct effect of SWC on net fruit but a negative indirect effect (-0.06). This indicates that uneven soil moisture distribution from BM indirectly inhibited yield, possibly via root hypoxia or nutrient leaching.

Solar radiation is another important factor for yield improvement (Bellasio and Griffiths, 2014). Under the BM method, although the total effect value of Rn on maize yield formation was 0.05, its direct effect was –0.13. This may be related to the continued accumulation of maize kernels even when Rn decreases with declining sunshine duration. Notably, the DM method exhibited a clear buffering capacity, effectively masking the potential direct negative effect of Rn and converting it into an indirect positive contribution. This indicates that DM not only enhances photosynthesis by optimizing the plant's physiological state but also improves the stability of the yield formation process and its resistance to environmental stress.

VPD and Tc can affect stomatal behavior (Fukuda et al., 2018), thereby influencing photosynthetic capacity and acting on the accumulation of organic substances. VPD and Tc only show indirect effects under DM, while both direct and indirect effects promote the formation of yield under BM, which may be a certain compensatory reaction of BM in the formation of yield. In addition, this study revealed that the total effect of the soil environment (SWC) on yield formation was greater under DM than that of the canopy environment (Rn, VPD, and Tc), whereas the reverse was true for BM. This indicates that a stable and suitable soil environment is highly advantageous for maize yield formation (Dang et al., 2022). Therefore, the most fundamental difference between the two irrigation systems lies in how water management modulates the yield formation pathway. Through precise water resource management, DM reconfigured the influence pathway of environmental factors on yield, enhancing the direct positive effects of LAI and SWC.

4.2. The implications and limitations of this study

The results of this study show that maize yield under DM increased by 12.85% compared with BM (Table 2). This increase falls within the range reported in similar studies, though the specific value is noticeably context-dependent. For example, the yield increase observed here is slightly lower than the 14.39% reported by Liu et al. (2023) in maize fields in Xinjiang, China, but higher than the 9.20% increase under drip irrigation relative to no irrigation obtained by Cui et al. (2024) through meta-analysis. Similarly, Sandhu et al. (2019) also demonstrated in Northwestern India that drip irrigation combined with straw mulch can achieve about a 14% yield increase compared with traditional furrow irrigation. The variation in the yield-enhancing effect of drip irrigation on maize is mainly influenced by multiple factors such as soil physicochemical properties, irrigation amount, and climatic condition (Cui et al., 2024; Irmak, 2024). For instance, higher soil bulk density can restrict root growth and resource acquisition, leading to reduced crop yield (Salem et al., 2021; Saudy et al., 2023), while different levels of water deficit under drip irrigation regimes can also cause varying degrees of yield reduction in maize (Irmak, 2024). Furthermore, although optimizing irrigation management under drip irrigation can improve maize yield, the extent of yield increase remains closely related to precipitation conditions (Żarski and Kuśmierek-Tomaszewska, 2023).

Previous studies have indicated that there may be an interaction between fertilization and drip irrigation that jointly affects maize yield (Ibrahim et al., 2016), although some research suggests that this interaction may not be significant in shaping yield (Żarski and Kuśmierek-Tomaszewska, 2023). A limitation of this study is the lack of systematic monitoring of nitrogen transport and transformation processes in the soil and plants, which prevented a clear understanding of the specific effects of water-nitrogen coupling on yield. Moreover, although this experiment lasted for eight years, the existing dataset may still be insufficient to fully capture the responses of yield to interannual climate variability and soil nutrient dynamics. Therefore, future research should involve more comprehensive spatiotemporal assessments, such as establishing experimental sites in different soil types and climatic regions, and pay greater attention to the responses of soil microbiomes and finer-scale plant physiological processes to drip irrigation practices.

Although this study was conducted at a specific site in Northwestern China, the mechanisms revealed—namely, achieving yield increases by improving water use efficiency, optimizing carbon and nitrogen metabolism, enhancing canopy photosynthetic capacity, and improving biomass allocation—reflect crops' general response to precision water management. Thus, the core principles underlying yield improvement under drip irrigation are likely applicable to other arid and semi-arid regions with similar constraints, such as high solar radiation, low precipitation, and deep groundwater tables. The findings of this study further demonstrate that large-scale adoption of the drip irrigation technology used here can significantly increase grain yield, thereby providing more reliable support for food security in water-scarce agricultural regions.

5. Conclusions

Based on an eight-year (2014–2021) field observation dataset from a typical arid region in Northwest China, this study has systematically revealed the comprehensive mechanism where DM achieves a 12.85% increase in maize yield than BM. The results demonstrate that this yield enhancement stems from the synergistic effect of physical, physiological, and ecological processes. Firstly, DM optimized the field microclimate conditions for maize growth through a high-frequency, low-volume irrigation mode, increasing Rn (+7.32%) and SWC (+21.60%), while effectively stabilizing VPD variations, thereby providing an excellent physical foundation for crop growth. Secondly, DM promoted more efficient coordination of the carbon and nitrogen metabolism at the plant level, raising the C/N in roots, stems, and leaves, thus allowing for improved nitrogen use efficiency and a greater capacity for directional transport of photoassimilates to the grains. Thirdly, DM enhanced the photosynthetic carbon sequestration capacity at the population level, resulting in GPP and NEP increase of 13.05% and 15.58%, respectively. Furthermore, by regulating the "source-flow-sink" relationship, DM enabled more efficient biomass allocation, facilitating a greater flow of photoassimilates towards the grains. Additionally, based on SEM analysis, this study found that DM restructured the yield formation pathway at the systemic level, buffered the negative impacts of environmental stresses on yield, and enhanced the direct positive effects of LAI and SWC on yield. Future research should further integrate climate change scenarios and crop physiological-ecological responses to decipher the mechanisms underlying sustained yield increase in precision agriculture, thereby promoting grain production enhancement and sustainable development of agricultural systems in arid regions.

CRediT authorship contribution statement

Sien Li: Writing – review & editing, Validation, Supervision. **Yahui Wang:** Writing – review & editing. **Enxiang Cai:** Writing – review & editing. **Mousong Wu:** Writing – review & editing. **Xinjie Shi:** Writing – review & editing. **Donghao Li:** Writing – review & editing. **Chunyu Wang:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2026.128057.

Data availability

Data will be made available on request.

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