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Optimising plastic-film mulching under drip irrigation to boost maize productivity through enhanced water and fertiliser efficiency in sub-humid regions

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Abstract: Global food security is increasingly threatened by the vulnerability of agricultural systems to climate variability, especially in sub-humid regions. Northeast China, a major maize-producing region, experiences low spring temperatures and erratic rainfall, which have prompted the widespread adoption of plastic-film mulching (PFM) combined with drip irrigation. However, systematic evaluations of how different PFM patterns affect crop productivity and resource use efficiency remain limited. This study systematically evaluated three PFM strategies – full ridge-furrow mulching (FM), ridge mulching (RM), and no mulching (NM) – in combination with 240 kg N/ha and a zero-nitrogen control under drip irrigation to determine their effects on maize (*Zea mays* L.) yield, water use efficiency (WUE), and nitrogen utilisation. Field experiments over two consecutive growing seasons assessed crop growth, dry matter (DM) accumulation, nitrogen dynamics, grain yield, and related efficiency parameters. Both FM and RM significantly enhanced early maize growth. At the seedling stage, FM and RM increased plant height by 43.0% and 40.1%, and leaf area index (LAI) by 141.4% and 120.4% over NM, respectively. During the same stage, DM accumulation increased by 228.9% (FM) and 224.9% (RM). These improvements reflected favourable soil hydrothermal conditions under PFM. Before heading, PFM treatments increased pre-anthesis DM accumulation by up to 19.6%, and at maturity, FM and RM raised DM by 6.1% and 5.1% over NM. PFM significantly improved grain nitrogen accumulation, with FM and RM increasing it by 31.0% and 26.9% over NM, respectively, and nitrogen harvest index (NHI), with FM and RM increasing it by 6.8% and 6.1% over NM, indicating enhanced nutrient translocation to grain. PFM also improved grain yield, with FM and RM increasing it by 15.0% and 13.5%, WUE by 17.2% and 15.7%, and nitrogen partial productivity by 16.8% and 14.1%. No significant differences in yield or WUE were observed between FM and RM. Fertilisation consistently enhanced these benefits without changing the relative efficiency ranking of treatments. Notably, the advantages of mulching diminished after the heading stage as temperature and rainfall increased. PFM (both FM and RM) under drip irrigation improves maize yield, water use, and nitrogen efficiency in sub-humid regions. This integrated practice offers a scalable and sustainable strategy to increase maize productivity and resource efficiency, supporting food security in regions facing similar climatic challenges.

Keywords: soil hydrothermal regulation; pre-anthesis development; climate-resilient agriculture; sustainable intensification; sub-humid region

Global food security is challenged by supply shortages and population growth. In 2023, approximately 2.33 billion people worldwide were moderately or severely food insecure (FAO 2024). In China, the decline in grain self-sufficiency, due to rising living standards, dietary shifts, and the COVID-19 pandemic, has heightened food security risks (Wang et al. 2020). Northeastern China, a key grain produc-

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tion base and one of the three globally recognised "Golden Maize Belts" alongside the U.S. Corn Belt and Ukrainian Maize Production Zone within the same mid-latitude agricultural corridor, cultivates spring maize (*Zea mays* L.) over 30% of the country's total planting area for this crop (Hou et al. 2021). This region is a strategic agricultural asset, significantly contributing to national food security through its high-yield grain production systems. However, frequent low temperatures and droughts in early spring severely constrain maize production in this region. In recent years, the "Water-Saving and Grain-Increasing Initiative" has promoted the widespread adoption of drip irrigation under plastic-film mulching (PFM) for maize in sub-humid Northeast China (Qi et al. 2019). While this technology effectively addresses insufficient accumulated temperatures during early growth stages and optimises irrigation and fertilisation throughout the growing season, theoretical research on its application in sub-humid regions of Northeast China lags behind practical implementation. The IPCC AR6 highlights the heightened climate sensitivity of semi-humid regions, yet research on their agricultural resilience remains scarce, underscoring urgent needs amid escalating extreme events (IPCC 2023).

The PFM technology has been widely adopted in China and globally, including in developing nations such as Kenya and India (Namdeo and Shrivastava 2021, Wang et al. 2021a). Various PFM patterns, such as flat planting with partial mulching, furrow planting with ridge mulching, continuous ridge planting with full mulching, and furrow planting with full mulching, have been developed to accommodate diverse rainfall and surface conditions (Ding et al. 2021, Dai et al. 2024, Fang et al. 2024). The PFM modifies solar radiation transmission, reflectance, and water vapour transfer, thereby affecting the thermal balance of the soil-crop system and influencing the soil environment and crop growth. Research shows that PFM patterns significantly affect soil hydrothermal conditions, with full ridge-furrow mulching offering superior water retention and temperature stability (Wei et al. 2020). Semi-mulching enhances root-zone soil temperature, water distribution uniformity, and soil enzyme activities (urease and phosphatase), resulting in higher leaf area index, root biomass, and root-to-shoot ratio compared to full or no mulching (Wang et al. 2016). However, the effects of PFM on soil moisture are not universally positive. In sub-humid regions or high-rainfall years, mulching may adversely affect soil moisture, suppressing root growth and nutrient uptake (Wang et al. 2018a). Thus, selecting appropriate PFM patterns based on specific environmental conditions is imperative.

Various PFM patterns are achieved by optimising soil environments and enhancing crop growth, dry matter accumulation, yield, and resource use efficiency. Sun et al. (2020) conducted a meta-analysis of 1 101 studies, revealed that PFM increases crop yields by 45.5% on average, with ridge-furrow mulching achieving the highest yield enhancement (84.7%). Correspondingly, water use efficiency (WUE) increased by 58.0% and 108.0% for the respective mulching practices. In semi-humid, drought-prone areas, full mulching and ridge mulching significantly elevated topsoil temperature and moisture content compared to flat planting without mulching, enhancing summer maize yields by 25.6% and 19.3%, and WUE by 41.2% and 25.9% (Yang et al. 2020). In high-altitude regions, wide mulching outperformed narrow mulching, increasing spring maize grain nitrogen accumulation by 17.8%, alongside improvements in nitrogen use efficiency (4.9%), nitrogen uptake efficiency (21.4%), agronomic nitrogen efficiency (23.5%), nitrogen partial factor productivity (12.2%), and nitrogen recovery efficiency (4.2%) (Fu et al. 2022). These findings underscore the critical role of optimal PFM patterns in enhancing crop productivity and resource efficiency. However, current research has not systematically evaluated the impact of PFM patterns on nitrogen use efficiency under drip irrigation in the sub-humid regions of Northeast China. This study evaluates three PFM patterns – full ridge-furrow mulching, ridge mulching, and non-mulching – in ridge-furrow systems, focusing on their impacts on spring maize's physiological and ecological responses. The field experiments were conducted over two consecutive years that experienced relatively favourable precipitation conditions. This study aims to identify optimal PFM strategies for maximising maize yield and resource-use efficiency under the specific conditions of sub-humid Northeast China. The findings provide a theoretical basis for sustainable and efficient maize production and can inform PFM optimisation in regions facing similar climatic and soil moisture regimes.

MATERIAL AND METHODS

Site description. The current study was conducted in Changchun, Jilin province, China, between 2017

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Table 1. Major soil properties (0–90 cm) in the experimental site

Depth (cm)	Organic carbon (g/kg)	Olsen-P (mg/kg)	Olsen-K (mg/kg)	BD (g/cm^3)	θ_{FC} (g/g)	Particle size (%) clay	silt	sand	Soil texture
0–30	15.7	50.9	135.4	1.35	0.26	12.9	72.9	14.2	Silt loam
30–60	12.3	20.9	136.2	1.47	0.27	12.7	72.9	14.4	Silt loam
60–90	11.9	16.1	147.3	1.42	0.30	12.4	73.6	14.0	Silt loam

BD – soil bulk density; θ_{FC} – field capacity

and 2018. The experimental site is located at coordinates 125°19'E, 43°38'N, with an elevation of 216 m a.s.l. This region is distinguished by a temperate sub-humid climate, featuring an average annual temperature of 4.8 °C and an average annual precipitation of 581 mm, as Bo et al. (2021) reported. The soil at the planting site was classified as a silt loam texture with 12.7% clay, 73.1% silt and 14.2% sand. Soil properties are detailed in Table 1. Field capacity (θ_{FC}, gravimetric water content at field capacity) was determined using disturbed soil samples from three field locations, collected with 100 cm^3 rings for bulk density (BD).

Experimental design. The study employed a randomised block design, comprising six treatments with three replicates. Treatments consisted of three plastic-film mulching (PFM) patterns – no mulching (NM), ridge mulching (RM), and full ridge-furrow mulching (FM) – each implemented with or without nitrogen fertilisation, resulting in six combinations: NM, RM, FM (with nitrogen), and CNM, CRM, CFM (without nitrogen). In all treatments, phosphorus and potassium fertilisers were applied at uniform rates to isolate the effect of nitrogen. Each plot covered an area of 28.8 m^2 (8 m × 3.6 m). All plots were prepared with 20 cm ridges and a line spacing of 60 cm.

For PFM treatments, a transparent polyethylene mulch film with a thickness of 0.008 mm was used. The mulch film and drip irrigation tape were simultaneously laid manually along the crop rows immediately after maize sowing (Figure 1). After seedling emergence, small holes were manually made in the film to allow the maize seedlings to emerge, and soil was applied around the holes to secure the film. To minimise environmental impact and residual plastic pollution, all mulch films were carefully and manually collected and removed from the field immediately after maize harvest.

For fertilisation, the recommended rates by the local agricultural extension agency were applied:

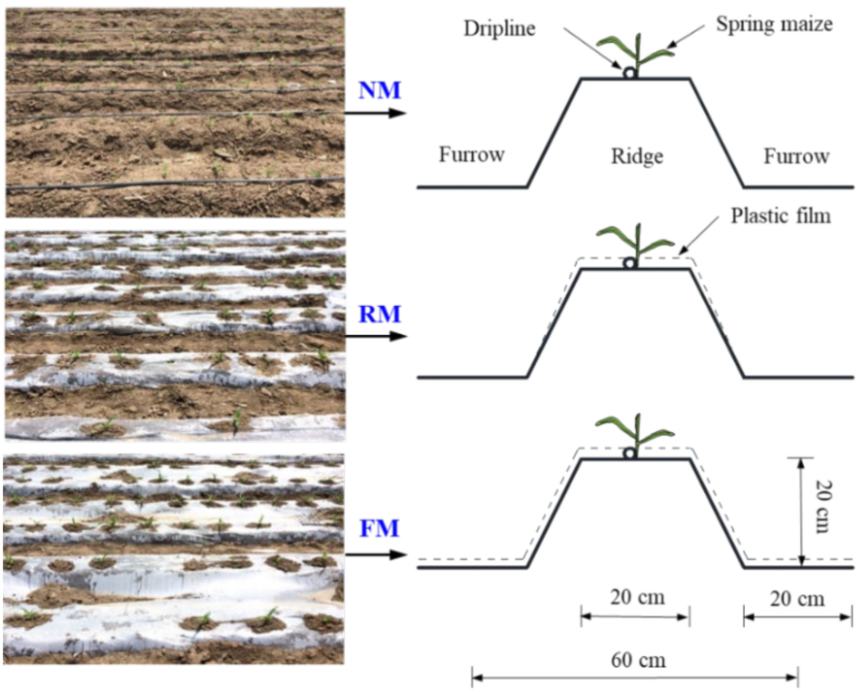

Figure 1. Cultivation systems and ridge-furrow configurations for maize. NM – no mulching; RM – ridge mulching; FM – full ridge-furrow mulching

240 kg N/ha, 24.2 kg P/ha, and 56.8 kg K/ha, based on the Technical Specifications for Soil Testing and Fertiliser Recommendation (Jilin Provincial Soil and Fertiliser Station 2016), widely used in Jilin province, China. These recommendations were further refined by integrating local high-yield cultivation experience to ensure that nutrient application was tailored to the actual soil fertility status and crop requirements. Before sowing, fertilisers were distributed evenly in the furrows from the previous year and incorporated into the soil using a rotary cultivator on the ridges. All fertilisers were applied as a one-time basal treatment, with no additional fertiliser applied during the maize growth period.

New holes were created at 30 cm intervals along the ridges, and a single maize seed (*Zea mays* L., cv. Jidong 59) was manually inserted into each hole on April 28, 2017, and April 26, 2018. Cv. Jidong 59 is a widely grown maize cultivar in Northeast China, selected for its strong adaptation to local conditions. It offers high and stable yields, good drought and lodging resistance, and broad disease resistance. With a growth period requiring about 2 750 °C accumulated temperature, it is well suited to the study area and supports high-density planting typical of regional practices. Based on recommendations from the local agency, a planting density of 55 555 plants/ha was adopted, with six rows of maize hand-sown in each plot.

Meteorological conditions and the irrigation system. An automatic weather station (JLC-CQ1, Licheng, China) positioned adjacent to the experimental field recorded rainfall amounts. The cumulative precipitation for the two seasons was 574.9 mm and 494.1 mm, respectively (Figure 2). The precipitation year types for spring maize during the growth period (April–September) were classified using the drought index (DI) method (Zhang et al. 2021), calculated as:

$$DI = ((p - M))/\sigma \quad (1)$$

where: p – growing season precipitation (mm) in the experimental year; M – long-term average precipitation (mm); σ – standard deviation of the long-term precipitation (mm). Year types were classified as follows: DI > 0.35 indicates a wet year; –0.35 ≤ DI ≤ 0.35 corresponds to a normal year, and DI < –0.35 designates a dry year. Based on historical precipitation data (1999–2018) for April–September, the long-term mean precipitation during the maize growth period was 513.0 mm, with a standard deviation of 129.2 mm. Accordingly, 2017 and 2018 were classified as wet and normal years, respectively.

A dripline was placed in the centre of each ridge, ensuring precise water application to each plot. The dripline featured an emitter spacing of 30 cm, with each emitter having a nominal flow rate of 1.38 L/h at a pressure of 0.1 MPa. Irrigation was triggered when the soil moisture under the non-mulching treatment dropped to 65–70% θ_{FC} (Kang et al. 2002). The total irrigation volume was 30 mm in 2017, increasing to 115 mm in 2018.

Monitoring and sampling. A gravimetric method was used to monitor and sample soil moisture content across all plots before and after sowing and harvesting. Soil samples were collected at a single position within each plot using a 5 cm diameter auger, from the midpoint of the ridge and furrow. Sampling depths were set at 10 cm increments to 30 cm, then 20 cm increments to 90 cm. Soil water contents were converted to soil water storage (SWS, mm) using bulk density. TRIME-T3 TDR (IMKO GmbH, Ettlingen, Germany) was used for *in situ* measurement of volumetric soil water content in the root zone. A 1.2 m T3 access tube was installed at the midpoint of both the furrow and the maize row in each plot. Weekly soil water content monitoring guided irrigation.

The seasonal evapotranspiration (ET, mm) was determined using the water balance equation (Kang et al. 2002), which accounts for water movement within the soil profile. The equation is as follows:

$$ET = \Delta SWS + P + I + G\text{-}R\text{-}De \quad (2)$$

where: ΔSWS – change in soil water storage (0–90 cm), calculated as the difference between initial and final values for each treatment; P – total precipitation (mm); I – applied irrigation amounts (mm); G – negligible upward groundwater flow into

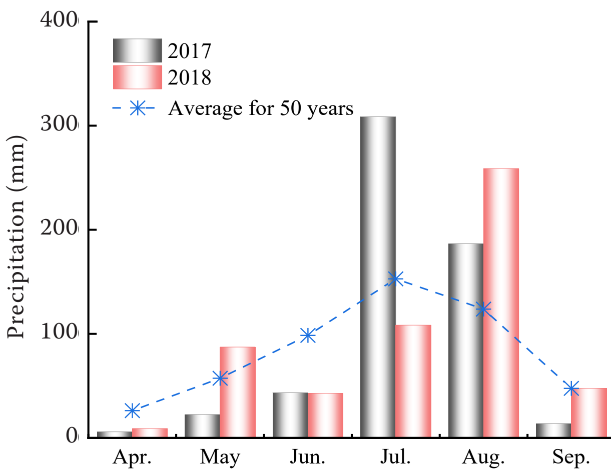

Figure 2. Seasonal rainfall distribution for maize cultivation

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the root zone, estimated from a groundwater table depth of about 4.22 m (Fu and Fu 2019); R – surface runoff, considered negligible due to ridges at both ends of each furrow preventing it; De – deep drainage (mm), estimated using Darcy's law.

The growth of spring maize was quantified by measuring leaf area index (LAI) and plant height at five stages: seeding stage (SS); jointing stage (JS); heading stage (HS); filling stage (FS), and maturity stage (MS). At the end of each growth stage, three representative maize plants per plot with uniform growth status were selected for measurement. Plant height was measured from the ground to the top of the leaf or terminal spikelet using a measuring ruler, as described by Jha et al. (2019). For LAI determination, the length and maximum width of all fully expanded leaves on each sampled plant were measured with a ruler. The individual leaf area was estimated by multiplying leaf length by maximum width and a shape factor of 0.74 to account for the typical morphology of maize leaves, as Peng et al. (2024) referenced. LAI was then calculated as the total green leaf area per plant divided by the ground area occupied by a single plant.

At each plot, two representative maize plants were harvested at a stubble height of approximately 0–1 cm above the soil surface at the end of each growth stage. The harvested plants were separated into stems, leaves, and grains; any fallen leaves within the sampling area were also collected and included in the analysis. To accurately determine aboveground dry matter (DM) weight, the fresh organs were heat-treated at 105 °C for 30 min to kill organisms and inactivate enzymes. Then, the material was oven-dried at 70 °C until a constant weight was reached. The dry matter weight of each plant organ was measured and then milled into a fine powder for nitrogen analysis. Nitrogen concentration in each organ was determined using a Kjeltec Analyser (Foss, Hilleroed, Denmark). Organ-specific nitrogen accumulation (kg/ha) was calculated by multiplying the nitrogen concentration by the dry matter content.

Using days after sowing as the independent variable, a Logistic equation was employed to establish a model for the dynamic accumulation of spring maize's aboveground dry matter (Chang et al. 2023):

$$DM = \frac{a}{1 + be^{-kT}} \tag{3}$$

where: T – number of days after sowing (d); DM – aboveground dry matter accumulation corresponding to time T (t/ha); a, b and k – undetermined parameters. The derivative of the Logistic equation gives the growth rate:

$$V = \frac{abke^{-kT}}{(1 + be^{-kT})^2} \tag{4}$$

The aforementioned equations can be used to determine the characteristic parameters of spring maize's DM accumulation (Gu et al. 2023).

During harvest, grain yield was quantified by manually harvesting two inner rows from two evenly spaced locations in each plot, totalling 2.16 m^2 (six plants per row) per location as a standardised sample. The harvested maize was then dried to 14% moisture content, according to industry standards, to determine the actual dry grain weight. Water use efficiency (kg/m^3) was calculated as the ratio of grain yield (Y, kg/ha) to the ET during the growing season. The equation is as follows (Zhu et al. 2025):

$$WUE = \frac{Y}{ET} \tag{5}$$

The nitrogen uptake efficiency was evaluated based on three parameters: nitrogen harvest index (NHI, %), applied nitrogen physiological efficiency (NPE, kg/kg), and nitrogen partial factor productivity (NPP, kg/kg). These were calculated using the following formulas:

$$NHI = \frac{Total\ N\ in\ grain}{Total\ N\ in\ aboveground} \times 100 \tag{6}$$

$$NPE = \frac{Y_N - Y_0}{U_N - U_0} \tag{7}$$

$$NPP = \frac{Y_N}{F_N} \tag{8}$$

where: Y_N – grain yield in the fertilised plot (kg/ha); Y_0 – grain yield in the non-fertilised plot (kg/ha); U_N – total plant nitrogen uptake in the fertilised plot at maturity stage (kg/ha); U_0 – total plant nitrogen uptake in the non-fertilised plot (kg/ha); F_N – amount of nitrogen fertiliser applied in the fertilised plot (kg/ha).

Statistical analysis. Data analysis was conducted using Excel 2021 (Microsoft Corp., Redmond, USA) and SPSS 20.0 (IBM Corp., Armonk, USA), and the figures were plotted using Origin 2024 (OriginLab Corporation, Northampton, USA). Plant height and LAI were repeatedly measured on the same plots across different growth stages and were analysed using repeated-measures ANOVA, with PFM pattern and fertilisation as between-subject factors and growth stage as the within-subject (repeated measures) factor. For variables measured only once per plot – such as nitrogen uptake, grain yield, and water and nitrogen use efficiency – a two-way ANOVA was conducted to assess the main and interaction effects of PFM pattern and fertilisation. Duncan's multiple range test (DMRT) was used for post-hoc comparisons at a significant level of 0.05 in all cases.

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RESULTS

Early growth dynamics. PFM and fertilisation markedly influenced the early growth of maize, as reflected by changes in LAI and plant height – two parameters closely related to initial crop vigour and subsequent yield potential. Over two growing seasons, both treatments significantly promoted maize growth, with plant height and LAI increasing rapidly from the seedling to heading stages (Table 2, Figure 3).

Plant height sharply increased during early development, then levelled off after heading. Compared with NM, both FM and RM enhanced plant height significantly, particularly at the seedling and jointing stages ($P < 0.01$ or $P < 0.001$). For example, at the seedling stage, FM and RM increased plant height by 43.0% and 40.1% over NM, respectively, while under non-fertilised conditions, CFM and CRM increased plant height by 39.9% and 37.4% compared to CNM. At the jointing stage, FM and RM increased plant height by 23.1% and 18.4% relative to NM, and CFM and CRM increased height by 15.7% and 15.2% over CNM. As temperatures and rainfall increased later in the season, differences in plant height among mulching treatments narrowed, and no significant differences were observed after heading ($P > 0.05$). No significant differences were detected between FM and RM at any growth stage. Fertilisation consistently resulted in taller plants than the non-fertilised controls at all stages ($P < 0.01$ or $P < 0.001$), with fertilised treatments producing significantly taller plants than non-fertilised ones ($P < 0.05$).

LAI followed a similar trajectory, increasing rapidly before heading and declining gradually. PFM and fertilisation significantly affected LAI, particularly during the seedling and maturity stages (Table 2). All mulching treatments produced significantly higher LAI values at the seedling stage than the non-mulched controls ($P < 0.05$). Under fertilisation, FM and RM increased LAI by 141.4% and 120.4% over NM, while CFM and CRM increased LAI by 161.6% and 153.9% compared to CNM. LAI decreased in all treatments post-seedling, and differences among mulching treatments diminished. At maturity, non-mulched treatments exhibited higher LAI than mulched treatments, with significant differences except under non-fertilised conditions in 2017. Under fertilisation, FM and RM reduced LAI by 22.9% and 24.4% compared to NM, while CFM and CRM decreased LAI by 19.4% and 25.9% relative to CNM. There was no significant difference in LAI between ridge-furrow mulching and ridge mulching treatments ($P > 0.05$). Fertilisation significantly increased LAI at all growth stages ($P < 0.05$ or $P < 0.001$) (Table 2).

Dry matter dynamics and nitrogen uptake. Both PFM and fertilisation led to notable improvements in biomass accumulation, DM dynamics, and nitrogen uptake – key factors for yield development. DM accumulation across all growth stages (Table 3, Figure 4) displayed a typical sigmoidal pattern: it increased slowly from seedling to jointing, then accumulated rapidly from jointing to filling, and finally stabilised at maturity. During the seedling stage, mulching treatments markedly increased DM (FM: 228.9%, RM:

Table 2. Repeated measures ANOVA (P-values) assessing the impact of fertilisation and plastic-film mulching (PFM) pattern on maize plant height and leaf area index

	Stage	Plant height		LAI	
		F	M	F	M
2017	SS	0.000***	0.000***	0.000***	0.000***
	JS	0.000***	0.001**	0.000***	0.634
	HS	0.000***	0.011*	0.000***	0.023*
	FS	0.000***	0.160	0.000***	0.584
	MS	0.000***	0.302	0.000***	0.010*
2018	SS	0.001**	0.000***	0.020*	0.000***
	JS	0.000***	0.000***	0.000***	0.143
	HS	0.000***	0.052	0.000***	0.295
	FS	0.000***	0.373	0.000***	0.772
	MS	0.000***	0.146	0.000***	0.001**

LAI – leaf area index; F – fertilisation; M – plastic-film mulching pattern; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$. SS – seeding stage; JS – jointing stage; HS – heading stage; FS – filling stage; MS – maturity stage

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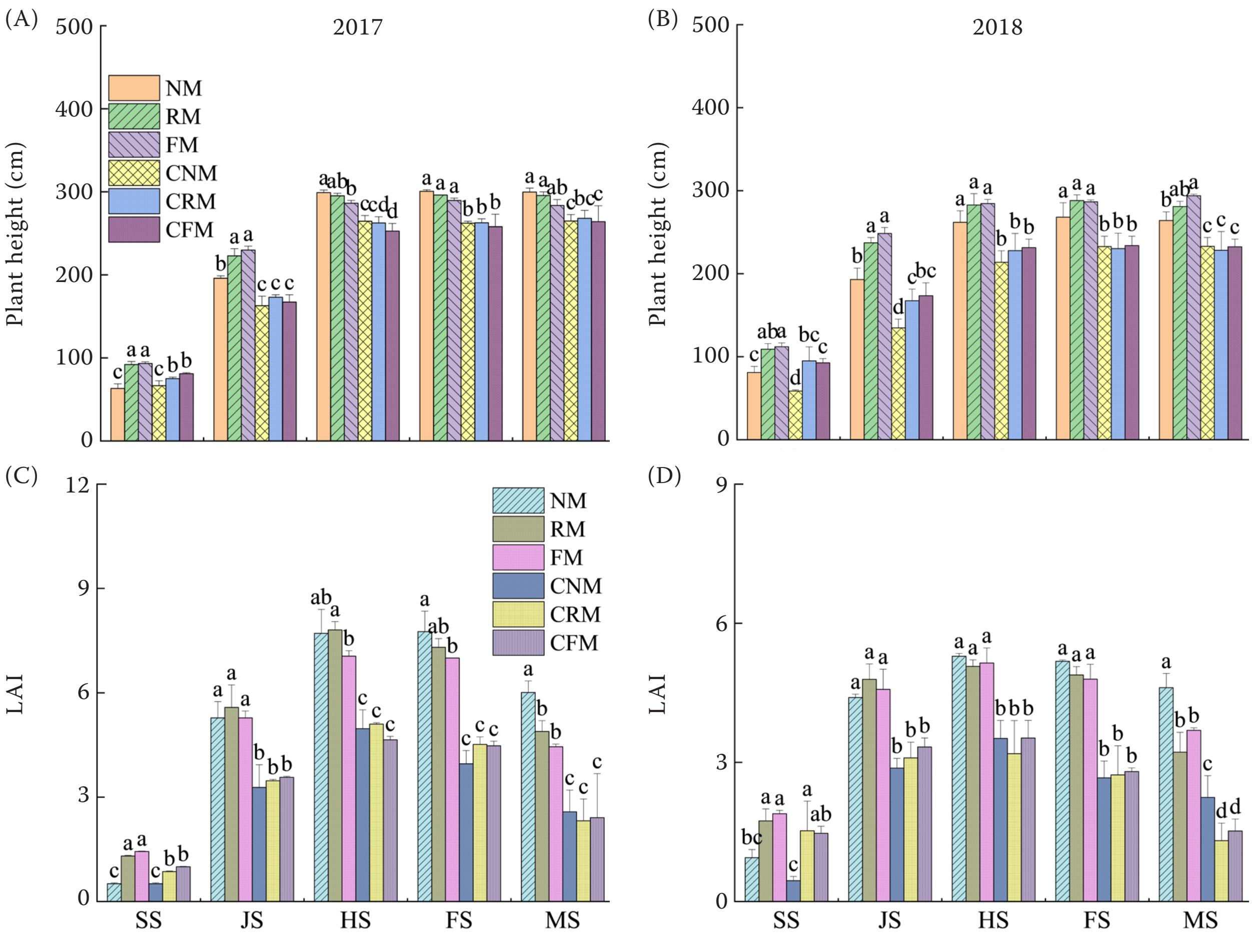

Figure 3. Maize plant height and leaf area index (LAI) at various growth stages. Error bars represent the standard deviation of the mean (*n* = 3). Different lowercase letters within each growth stage indicate significant differences ($P < 0.05$) among treatments, as determined by Duncan's multiple range test (DMRT). SS – seeding stage; JS – jointing stage; HS – heading stage; FS – filling stage; MS – maturity stage; NM – no mulching; RM – ridge mulching; FM – full ridge-furrow mulching; CNM – no mulching and no fertilising; CRM – ridge mulching and no fertilising; CFM – full ridge-furrow mulching and no fertilising

Table 3. Plant biomass (g/plant) across various treatments at each growth stage

Treatment	2017					2018				
	SS	JS	HS	FS	MS	SS	JS	HS	FS	MS
NM	10.7^{d}	204.1^{ab}	295.0^{ab}	423.9^{ab}	531.8^{a}	15.1^{c}	169.5^{b}	266.6^{b}	369.3^{a}	371.2^{a}
RM	38.7^{a}	241.6^{a}	353.1^{a}	461.1^{a}	536.0^{a}	43.5^{a}	202.8^{a}	312.7^{a}	397.3^{a}	413.4^{a}
FM	36.3^{a}	235.3^{a}	337.9^{a}	508.7^{a}	542.0^{a}	48.1^{a}	199.5^{a}	302.4^{ab}	397.6^{a}	416.5^{a}
CNM	13.4^{c}	156.4^{b}	215.3^{b}	230.5^{d}	261.3^{b}	9.9^{d}	101.1^{c}	137.4^{d}	189.0^{b}	195.4^{c}
CRM	25.3^{b}	158.9^{b}	227.0^{b}	332.8^{c}	350.9^{b}	26.7^{b}	101.8^{c}	197.6^{c}	212.6^{b}	241.1^{bc}
CFM	23.5^{b}	183.6^{b}	228.4^{b}	347.8^{bc}	385.5^{b}	29.4^{b}	104.0^{c}	199.0^{c}	214.0^{b}	251.9^{b}
ANOVA (*P*-values)										
F	0.023*	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
M	0.000***	0.206	0.350	0.011*	0.284	0.000***	0.285	0.003**	0.266	0.016*

SS – seeding stage; JS – jointing stage; HS – heading stage; FS – filling stage; MS – maturity stage; F – fertilisation; M – plastic-film mulching pattern; NM – no mulching; RM – ridge mulching; FM – full ridge-furrow mulching; CNM – no mulching and no fertilising; CRM – ridge mulching and no fertilising; CFM – full ridge-furrow mulching and no fertilising Significant differences at α = 0.05 level are denoted by different lowercase letters in each column; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

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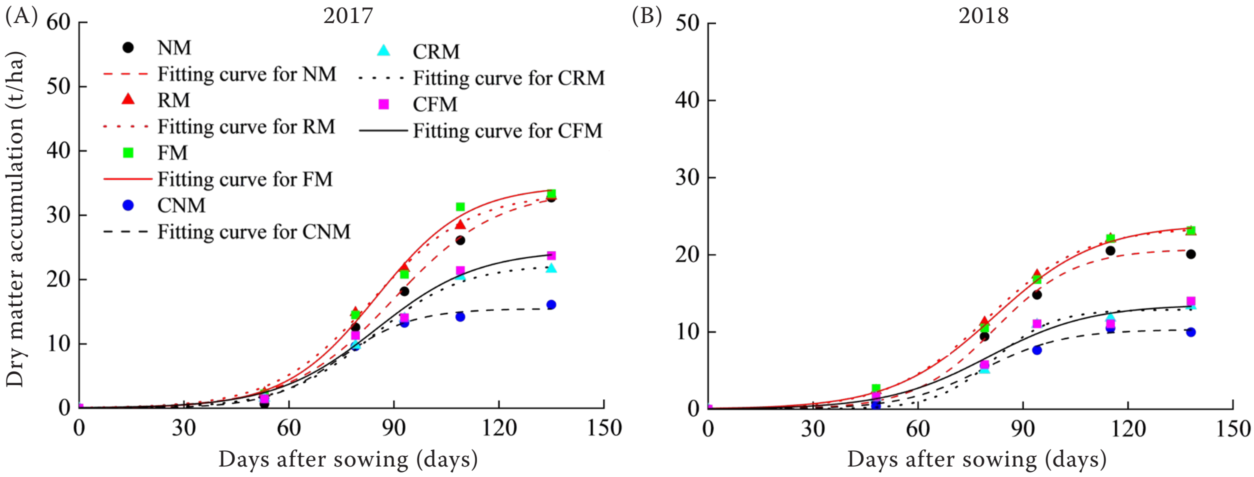

Figure 4. Fitting curves of aboveground dry matter accumulation of spring maize by logistic model under different treatments. NM – no mulching; RM – ridge mulching; FM – full ridge-furrow mulching; CNM – no mulching and no fertilising; CRM – ridge mulching and no fertilising; CFM – full ridge-furrow mulching and no fertilising

224.9% over NM; CFM: 136.2%, CRM: 129.3% over CNM; $P < 0.001$). As the season advanced, the advantages of mulching diminished, yet before heading, fertilised mulching treatments maintained 15.3–19.6% higher DM than non-mulched treatments. At maturity, mulched plots still had higher biomass, with FM achieving the highest mean DM (479.3 g/plant). FM and RM increased DM by 6.1% and 5.1% over NM, while CFM and CRM showed increments of increased DM by 39.6% and 29.6% compared to CNM. Fertilisation significantly promoted DM accumulation at all growth stages ($P < 0.05$ or $P < 0.001$), with fertilised plots outperforming non-fertilised plots ($P < 0.05$).

Table 4 shows the logistic model parameters describing DM accumulation dynamics under different

Table 4. Parameters of logistic model of aboveground dry matter accumulation of spring maize under different treatments

	Treatment	R^2	T_{begin}	T_{end}	ΔT	ΔD	T_{max}	V_{max}	D_{max}
				(days)		(t/ha)	(day)	(t/ha/day)	(t/ha)
2017	NM	0.987***	70.4	109.5	39.1	19.3	89.9	0.572	33.5
	RM	0.996***	65.3	102.0	36.8	19.6	83.6	0.600	33.9
	FM	0.989***	67.9	102.2	34.3	20.0	85.0	0.665	34.6
	CNM	0.992***	61.0	88.1	27.2	8.9	74.5	0.375	15.5
	CRM	0.990***	66.6	100.3	33.8	12.9	83.5	0.436	22.4
	CFM	0.979***	65.9	104.1	38.2	14.2	85.0	0.424	24.6
2018	NM	0.994***	66.5	96.7	30.3	12.0	81.6	0.452	20.8
	RM	0.999***	61.4	98.0	36.6	13.6	79.7	0.424	23.5
	FM	0.998***	62.0	100.7	38.7	13.8	81.4	0.408	24.0
	CNM	0.985***	63.3	94.0	30.6	6.0	78.6	0.222	10.3
	CRM	0.970***	70.3	92.8	22.5	7.4	81.5	0.377	12.9
	CFM	0.952**	60.5	98.7	38.2	7.8	79.6	0.234	13.6

T_{begin} – beginning time of rapid accumulation; T_{end} – end time of rapid accumulation; ΔT – time corresponding to the maximum accumulation; ΔD – rapid accumulation quantity; T_{max} – time corresponding to the maximum accumulation rate; V_{max} – maximum accumulation rate; D_{max} – maximum accumulation; d – days after sowing; Significant differences at α = 0.05 level are denoted by different lowercase letters in each column; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; NM – no mulching; RM – ridge mulching; FM – full ridge-furrow mulching; CNM – no mulching and no fertilising; CRM – ridge mulching and no fertilising; CFM – full ridge-furrow mulching and no fertilising

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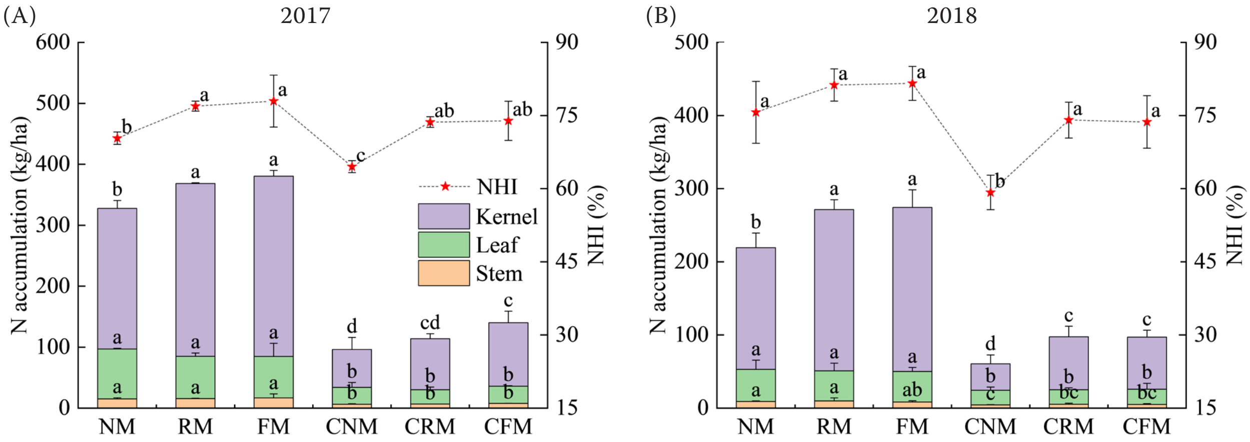

Figure 5. Nitrogen (N) accumulation in kernels, leaves, and stems, and nitrogen harvest index (NHI) at physiological maturity for various treatments. Error bars represent the standard deviation of the mean (n = 3); Significant differences at α = 0.05 level are denoted by different lowercase letters. NM – no mulching; RM – ridge mulching; FM – full ridge-furrow mulching; CNM – no mulching and no fertilising; CRM – ridge mulching and no fertilising; CFM – full ridge-furrow mulching and no fertilising

treatments. All equations had coefficients of determination (R^2) above 0.950, with high significance (P < 0.01 or P < 0.001), confirming the model's accuracy in simulating DM dynamics. Mulching treatments (FM: 29.3 t/ha; RM: 28.7 t/ha) reached higher theoretical maximum DM compared to non-mulching (27.1 t/ha), representing increases of 8.1% and 5.9%, respectively. The peak DM accumulation rates appeared during the heading stage (74.5–89.9 days after sowing), and FM and RM increased the accumulation rate (ΔD) by 7.6% and 5.7% over NM.

At maturity, nitrogen was mainly distributed in grains, followed by leaves and stems (grains > leaves > stems; Figure 5). PFM significantly improved grain nitrogen accumulation (FM: 260.0 kg/ha; 31.0% over NM; RM: 26.9% over NM; P < 0.05). In non-fertilised plots, CFM and CRM increased grain nitrogen by 77.6% and 58.3% over CNM. Total plant nitrogen uptake showed a similar pattern, with FM highest (327.4 kg/ha; 19.7% over NM). Fertilisation significantly increased nitrogen accumulation in all plant organs (P < 0.05).

Mulching also increased the NHI. Mulching treatments resulted in significantly higher NHI than non-mulching treatments (P < 0.05), except for fertilised treatments in 2018, with the order FM > RM > NM (Figure 5). This suggests that mulching enhances nutrient translocation from vegetative tissues and roots to grains. FM achieved the highest NHI of 79.8%. FM and RM increased NHI by 6.8% and 6.1% over NM, while CFM and CRM increased NHI by 12.0% and 11.9% compared to CNM. Fertilised treatments consistently showed higher NHI than non-fertilised treatments, with increases of 5.2–11.1% across seasons.

Grain yield, water use efficiency, and nitrogen use efficiency. With increasing plastic-film coverage, grain yield steadily improved (Figure 6). No significant difference (P > 0.05) was observed between FM and RM, but both treatments significantly outperformed NM (P < 0.05). Both PFM and fertilisation significantly enhanced yield, with FM

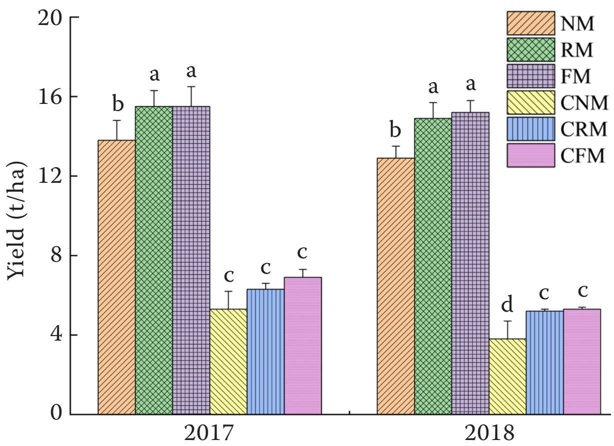

Figure 6. Maize grain yield response to various treatments. Error bars represent the standard deviation of the mean (n = 3); Different lowercase letters within each year indicate significant differences among treatments at α = 0.05 (Duncan's multiple range test (DMRT)). NM – no mulching; RM – ridge mulching; FM – full ridge-furrow mulching; CNM – no mulching and no fertilising; CRM – ridge mulching and no fertilising; CFM – full ridge-furrow mulching and no fertilising

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Table 5. Soil water storage changes (ΔSWS) in the 0–90 cm profile from sowing to harvest, evapotranspiration (ET), water use efficiency (WUE), applied nitrogen physiological efficiency (NPE), and nitrogen partial factor productivity (NPP) for various treatments

Treatment	2017					2018				
	ΔSWS	ET	WUE	NPE	NPP	ΔSWS	ET	WUE	NPE	NPP
	(mm)		(kg/ha/mm)	(kg/kg)		(mm)		(kg/ha/mm)	(kg/kg)	
NM	-22.4^{a}	627	19.0^{b}	31.5	49.9^{b}	33.1^{a}	576	19.3^{b}	48.9	46.4^{b}
RM	-12.1^{a}	617	21.6^{a}	28.6	55.9^{a}	40.8^{a}	568	22.7^{a}	46.8	53.9^{a}
FM	-20.1^{a}	625	22.0^{a}	31.5	57.5^{a}	35.3^{a}	574	22.9^{a}	48.4	54.9^{a}
CNM	-10.6^{a}	609	7.6^{d}	–	–	42.9^{a}	566	5.9^{d}	–	–
CRM	-11.5^{a}	616	9.9^{c}	–	–	40.3^{a}	569	8.5^{c}	–	–
CFM	-12.8^{a}	618	10.1^{c}	–	–	33.7^{a}	575	7.9^{c}	–	–
ANOVA (*P*-values)										
F	0.143	0.143	0.000***	–	–	0.720	0.720	0.000***	–	–
M	0.196	0.196	0.006**	0.523	0.041*	0.780	0.780	0.000***	0.864	0.015*

F – fertilisation; M – plastic-film mulching pattern; Significant differences at α = 0.05 level are denoted by different lowercase letters in each column; ; $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$; NM – no mulching; RM – ridge mulching; FM – full ridge-furrow mulching; CNM – no mulching and no fertilising; CRM – ridge mulching and no fertilising; CFM – full ridge-furrow mulching and no fertilising

achieving the highest mean value (15.4 t/ha). FM and RM increased yield by 15.0% and 13.5% over NM; CFM and CRM increased yield by 32.4% and 25.1% over CNM. However, the yield advantage of PFM was influenced by annual rainfall. In 2017 (the humid year), both CFM and CRM showed only a non-significant increase in grain yield compared to CNM ($P > 0.05$), despite numerical improvements. In contrast, in 2018 (the normal year), CFM and CRM significantly increased yield relative to CNM even without nitrogen application. These results suggest that the positive effect of PFM on yield may be limited under humid conditions. However, these findings are based on a single site, and further multi-year, multi-site studies are needed to validate the generalisability of these patterns.

Evapotranspiration (ET) showed no significant response to PFM or fertilisation (Table 5; $P > 0.05$). However, both factors significantly increased water use efficiency (WUE; $P < 0.01$ or $P < 0.001$). FM and RM did not differ significantly in WUE, but both outperformed NM (FM: 22.5 kg/ha/mm; 17.2% and 15.7% increases over NM, respectively). Under non-fertilised conditions, CFM and CRM improved WUE by 33.3% and 36.3% over CNM. Non-fertilised treatments consistently showed lower WUE than fertilised treatments ($P < 0.05$).

PFM did not significantly affect NPE ($P > 0.05$), indicating that the efficiency of converting applied nitrogen into yield remained stable across mulching strategies. However, PFM significantly increased NPP ($P < 0.05$), with NPP values rising as plastic-film coverage increased. FM consistently resulted in the highest NPP (56.2 kg/kg), followed by RM and NM (FM > RM > NM). FM and RM did not differ significantly in NPP ($P > 0.05$), but both were significantly higher than NM ($P < 0.05$). Compared to NM, FM and RM increased NPP by 16.8% and 14.1%, respectively.

DISCUSSION

Effects of PFM on maize morphological development. PFM effectively promotes early canopy establishment and plant height, which are critical for optimising crop structure and resource capture in maize. Improved soil temperature and moisture regimes under mulching – well documented in both northeast and semi-arid regions (Qi et al. 2019, Zhang et al. 2019, Zhao et al. 2022, Li et al. 2023) – contribute to this enhanced early growth. In the present study, FM and RM increased plant height by up to 18.4–43.0% and LAI by up to 120.4–141.4% during early stages compared with non-mulched controls. These early growth advantages facilitate more vigorous canopy development and greater photosynthetic capacity.

However, the effects of mulching on crop growth depend on the mulching configuration. For exam-

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ple, Liu (2023) found that in semi-arid regions, full mulching significantly improved spring maize plant height and LAI, whereas partial mulching had moderate effects. Our results are consistent with these findings: increased mulching coverage promoted early-stage plant growth, and plant height and LAI were positively correlated with the mulched area. This effect is attributed to improved soil warming and moisture conservation with greater mulching coverage (Gao et al. 2021).

During the growing season, differences in plant height and LAI among mulching treatments diminished. This convergence was likely due to elevated ambient temperatures during mid-to-late growth stages, film degradation, and increased mutual shading, which collectively reduced the benefits of mulching (Wang et al. 2018b). Notably, in our study, PFM consistently resulted in a significant reduction in LAI at maturity, with the decline being more pronounced under higher mulching coverage. Importantly, this reduction was observed across both years and under both fertilised and unfertilised conditions (Figure 3), indicating that decreased LAI at maturity cannot be solely explained by excessive nitrogen application.

Notably, in our study, PFM significantly reduced LAI at maturity, with greater declines observed under higher mulching coverage. This reduction was consistent across both years and under both fertilised and unfertilised conditions (Figure 3), suggesting that it cannot be solely attributed to excessive nitrogen application. This pattern may be explained by accelerated morphological development under PFM, which extends the reproductive growth phase (Hu et al. 2020). In contrast, delayed development under NM may have led to prolonged leaf retention at maturity as a compensatory strategy. These dynamics reflect the complex interaction between crop growth rate, canopy structure, and nutrient remobilisation. Alternatively, excessive nitrogen application has been reported to accelerate leaf senescence by increasing pre-anthesis nutrient remobilisation to grains (Liu et al. 2017). While this mechanism may have contributed, our results indicate that growth stage progression, rather than nitrogen effect alone, was the dominant factor shaping LAI patterns at maturity. Overall, these findings highlight the complex interplay between mulching, nitrogen management, and crop phenology. To maximise yield and resource efficiency, farmers should consider moderate N application rates and monitor crop nutrient status throughout the season. Sustainable maize production in sub-humid regions can be further enhanced by integrating site-specific, moderate fertilisation guided by soil testing, which helps avoid nitrogen overuse and reduces environmental risks. Additionally, management practices should be adapted to local rainfall variability and soil characteristics to optimise resource use and yield stability.

Effects of PFM on dry matter accumulation and yield formation. Film mulching improves the crop-soil hydrothermal relationship, accelerates morphological development, and extends the reproductive growth period, which together enhance dry matter accumulation and yield (Li et al. 2021, Liang et al. 2023). In this study, PFM significantly increased DM by 224.9–228.9% during early growth stages and by 5.1–6.1% at maturity, resulting in a yield increase of 14.0–15.0%. Similar results have been reported by Zhang et al. (2018) in drip-irrigated fields in Northeast China, where film mulching increased mature-stage biomass by 4.8–6.9% and yield by 5.9–8.8%. Long-term studies indicate that full-film mulching is more effective than half-film mulching in stabilising spring maize production across varying rainfall patterns and soil moisture conditions, due to superior thermal retention and evaporation suppression (Zhang et al. 2022a, Zheng et al. 2022). Li et al. (2017) also demonstrated that wide-film mulching resulted in greater improvements in dry matter and productivity than row-based mulching in Northeast China. In our study, expanded mulching coverage enhanced DM accumulation and yield formation at maturity. FM with two years of consecutive fertilisation achieved the highest yield (15.4 t/ha) and DM per plant (479.3 g/plant), followed by RM, which is consistent with previous findings.

Dry matter accumulation is fundamental for grain formation and closely linked to yield development. During grain filling, nutrients are primarily allocated to the ear, with substantial translocation from vegetative tissues (Hou et al. 2021). Pre-anthesis DM accumulation is particularly important for ear differentiation (Uribelarrea et al. 2007). In this study, film mulching markedly increased pre-anthesis DM accumulation by 15.3–19.6% over two consecutive years, promoting greater nutrient allocation to the ear and subsequent yield increases. Liang et al. (2023) similarly highlighted that early-stage DM accumulation significantly affects yield in arid regions, attributing this effect to improved vegetative growth supporting reproductive development. Although post-anthesis DM accumulation differed little among

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mulching treatments, film mulching significantly increased grain nitrogen accumulation while reducing LAI. This suggests that mulching promoted nutrient translocation from leaves to grains without compromising post-anthesis nutrient accumulation.

Previous studies have shown that film mulching not only enhances dry matter accumulation in plant organs but also optimises grain yield components by increasing grain proportion and improving ear traits (Zhang et al. 2021, Liu 2023). Our results support these findings, as mulching significantly increased the nitrogen harvest index. Over two years, full mulching and ridge mulching increased NHI by 9.4% and 9.0%, respectively, compared to treatments without mulching, indicating enhanced nitrogen allocation to grains. Additionally, previous research has shown that mulching improves yield components by increasing 100-grain weight and reducing bare tip length (Bo et al. 2021). Overall, film mulching in semi-humid Northeast China enhances grain yield through three synergistic mechanisms: increasing early-stage DM accumulation, promoting post-anthesis nutrient translocation to grains, and optimising yield-related traits.

Despite being conducted over one wet year and one normal year at a single site, these findings provide valuable insights for optimising maize production in similar sub-humid regions. Nonetheless, it should be recognised that the generalisability of these results is subject to the limitation of the study's duration and location. Future research should validate these results across a wider range of climatic conditions, soil types, and management systems to better understand the broader applicability and to optimise mulching and fertilisation strategies in diverse sub-humid agroecosystems.

Effects of PFM on water and nitrogen utilisation. Current studies on the effects of PFM on total crop water consumption still remains inconclusive. Most studies report that mulching reduces ET (Ramos et al. 2024). However, some have found negligible differences between mulched and non-mulched treatments (Qi et al. 2019, Wang et al. 2021b). For instance, Zhang et al. (2018) observed only a 3.9–5.2% reduction in ET for drip-irrigated spring maize with PFM in Northeast China. In our study, differences in total water consumption among mulching patterns were minimal. FM and RM reduced ET by only 0.4–1.6% compared to NM over two years, consistent with previous findings. This may be due to PFM altering water consumption patterns by suppressing soil evaporation while increasing crop transpiration through enhanced sensible heat flux (Ramos et al. 2024). Additionally, frequent rainfall during the mid-to-late growth stages may diminish the effect of mulching on soil evaporation. Concurrently, declining LAI reduces transpiration rates, together resulting in negligible ET differences between mulched and non-mulched conditions.

The ridge-furrow PFM system improves WUE by reducing soil evaporation and increasing the availability of rainfall and stored soil water (Wang et al. 2021a). It also enhances yield through improved crop growth (Zhang et al. 2020a, Wang et al. 2021c). Our results showed that FM and RM increased WUE by 17.2% and 15.7%, respectively, compared to NM over two years – aligning with regional studies (Zhang et al. 2020c, Liang et al. 2023). This suggests that mulching enhances farmland water efficiency in this region, as WUE is positively correlated with mulching coverage. The limited differences in ET under frequent mid-to-late season rainfall, combined with significant yield increases from mulching, collectively result in higher WUE. Both mulching and fertilisation significantly affected WUE, and their effects were modulated by rainfall patterns (Zhang et al. 2020b, 2022b). As our two-year trials coincided with high-rainfall years and locally recommended fertilisation rates, future research should investigate mulching effects across diverse rainfall and fertilisation regimes to optimise water-saving and yield benefits in the semi-humid region of Northeast China.

PFM led to substantial increases in grain yield, which is the primary goal of agronomic management. In our study, both FM and RM significantly improved grain yield compared to NM, with increases of 15.0% and 13.5% under local recommended fertilisation. Importantly, these yield improvements were achieved without a significant change in NPE among treatments, indicating that the efficiency of converting applied nitrogen into grain yield remained stable across mulching strategies. However, NPP was significantly higher in mulched treatments, reflecting greater yield per unit of nitrogen input. While previous studies have reported that excessive fertilisation can reduce nitrogen use efficiency and increase environmental risks (Ma et al. 2023), our results do not provide direct evidence that reducing fertiliser rates under mulching would maintain comparable yields, as lower fertilisation levels were not tested in this study. Both FM and RM increased NPP by 16.8% and 14.1%, respectively, indicating that film

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mulching improves nitrogen fertiliser productivity and enhances economic benefits under local fertilisation rates. This result aligns with previous studies, where full ridge-furrow mulching and ridge mulching increased nitrogen use efficiency by 8.9% and 7.6%, and agronomic nitrogen efficiency by 7.9% and 4.0%, respectively (Bo et al. 2021). Notably, NPE did not differ significantly among mulching methods, suggesting that increased nitrogen uptake contributed similarly to grain yield under local fertilisation, regardless of mulching approach. Therefore, our findings support the conclusion that combining plastic film mulching with appropriate fertilisation enhances yield and input productivity. However, whether further optimisation of fertilisation – such as reducing nitrogen input – can sustain yield under mulching requires additional research involving a broader range of fertiliser rates.

While PFM improves productivity, its long-term environmental impact, especially plastic residue accumulation, warrants attention. Recent studies suggest biodegradable films offer comparable benefits with reduced environmental risks (Zhang et al. 2025). Future research should evaluate these alternatives under sub-humid conditions.

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