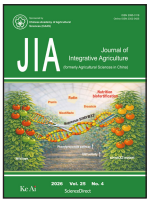
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RESEARCH ARTICLE

# Biodegradable mulch films support root proliferation and yield in water-saving rice production

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**Highlights**

- Biodegradable mulch films enhanced the soil conditions in water-saving rice production.
- Enhanced spatial distribution of the root system improved rice resistance to stunting.
- Optimized root development contributed to rice productivity and sustainability with biodegradable mulch films.

**Abstract**

Water-saving rice systems must maintain yield targets while reducing water consumption. Applying biodegradable film to cover the soil surface reduces water loss through evapotranspiration, establishing a warmer, more humid microenvironment for rice growth compared to traditional paddy rice systems. This study examined soil water regimes for rice production in Northeast China, comparing rice growth with and without biodegradable mulch film under continuous flooding, drip irrigation, and controlled irrigation conditions. The implementation of biodegradable mulch film elevated soil temperature and sustained soil moisture during early rice development. Continuous flooding with biodegradable mulch film yielded the highest rice production (9.4 Mg ha$^{-1}$) and net profit of approximately 11,800 CNY ha$^{-1}$. Drip irrigation with biodegradable mulch film achieved maximum water efficiency, demonstrating the highest water productivity (1.25 kg m$^{-3}$) and minimum water consumption (235 mm). Root length, weight, and surface area in the 0–40 cm soil layer exhibited positive correlations with water productivity, shoot dry matter, and yield, indicating that root morphological characteristics, particularly during the panicle initiation stage, enhanced rice production and water conservation. The findings demonstrate that biodegradable mulch film created favorable soil conditions for root proliferation, enabling higher yields in water-saving rice systems.

**Keywords:** biodegradable mulch film, water-saving rice, root characteristics, grain yield, crop water productivity

## 1. Introduction

Rice (*Oryza sativa* L.), a globally significant cereal crop, requires a 40% increase in production by 2040 to meet the food demands of the expanding world population (Liu *et al.* 2021). Currently, approximately 36% of rice cultivation depends on irrigation, which presents a potential yield-limiting factor due to global water scarcity, further intensified by erratic rainfall patterns associated with climate change (Gao *et al.* 2023b). Water-saving rice systems utilize various agronomic innovations for water conservation. A notable innovation is plastic mulch film technology, which covers the soil surface with a plastic film layer to reduce evaporative soil moisture losses, enhance soil temperature, and suppress weed growth (Lee *et al.* 2019; Chen *et al.* 2021; Zhao *et al.* 2024). According to a global meta-analysis, water-saving rice systems with plastic mulch film can increase yield

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(0.4 Mg ha$^{-1}$ yr$^{-1}$) and water productivity (0.2 kg m$^{-3}$) (Sun *et al.* 2020). However, plastic film presents challenges, including hindering nitrogen fertilizer and nutrient input delivery during late vegetative and flowering growth stages (Tao *et al.* 2014) and creating disposal difficulties, contributing to plastic residues and microplastic pollution in farmland (Sintim and Flury 2017).

Biodegradable film presents an alternative solution that provides mulching benefits without contributing to farmland plastic pollution (Serrano-Ruiz *et al.* 2021). These films degrade during crop growth, addressing the challenges of fertilizer application and film recycling (Gao *et al.* 2023a). Consequently, water-saving rice production may be achieved using biodegradable mulch film as a sustainable water conservation practice (Zhang *et al.* 2017a). The effects of biodegradable mulch film on agronomic and environmental outcomes in rice production include (Gu *et al.* 2020; Nelson *et al.* 2020; Tofanelli and Wortman 2020): (1) increasing crop grain yields by 16–21%; (2) improving crop water productivity by 17–25%; (3) mitigating $CH_4$ emissions by 53–76%; and (4) no change in g $N_2O$ emissions. These findings warrant evaluation of biodegradable mulch film's effects on rice growth and yield in water-saving systems.

Root systems play a crucial role in sensing environmental heterogeneity and acquiring limited water resources in rice cultivation. Specifically, root length, weight, and surface area directly influence the proliferation and functions of the entire root system (Santos-Medellín *et al.* 2021). Under drought stress conditions during growth periods, biodegradable mulch film partially improves soil conditions and maintains root activity during drought-sensitive growth stages, such as tillering and panicle initiation (Zhang *et al.* 2017a; Chen *et al.* 2020). Root systems facilitate increased rice capacity for water and nutrient uptake (Subrahmaniyan and Mathieu 2012; Sun *et al.* 2018), resulting in enhanced photosynthetic rates and greater biomass accumulation (Shangguan *et al.* 2024). For example, in drip irrigation systems, biodegradable mulch film enhances cotton root length density at the tillering stage, subsequently increasing yields (Chen *et al.* 2020). However, quantitative assessments of biodegradable mulch film effects on root growth and development in water-saving rice production remain limited (Zhang *et al.* 2017b), particularly across flood and drip-irrigated cultivation conditions. Additionally, detailed longitudinal studies examining root architectural changes throughout the rice-growing season under biodegradable mulch film and varying water regimes are scarce, limiting understanding of developmental plasticity (Li *et al.* 2020; Fang *et al.* 2022). Studies effectively connecting quantified root trait improvements under biodegradable mulch film to definitive, mechanistic explanations for observed yield variations remain insufficient, especially under field conditions across diverse environments.

The objectives of this study were to: (1) examine biodegradable mulch film effects on soil environment (temperature and water content); (2) determine how biodegradable mulch film on the soil surface affects root growth in the soil profile (to 40 cm depth); and (3) analyze the relationship between root characteristics, grain yield, and water productivity in water-saving rice systems.

## 2. Materials and methods

### 2.1. Site description

The field experiment was conducted in rice fields situated in Jalaid Banner, Inner Mongolia (46°41′47′′N, 123°6′52′′E, altitude 170 m), Northeast China, during the 2021 and 2022 growing seasons. The site exhibited a typical mid-temperate continental monsoon climate, characterized by annual rainfall of 429 mm, annual potential evapotranspiration of 1,960 mm and a groundwater table>7 m deep, excluding capillary rise (Zhang *et al.* 2017b). The soil composition in the 0–20 cm tillage layer comprised 13% clay, 47% silt, and 40% sand. The soil type, base nutrient content, and soil physicochemical properties were described in Gao *et al.* (2023a). Flood and drip irrigation experimental plots were adjacent and separated by a walkway.

The growth periods of rice varied between flood and drip-irrigated cultivation conditions as shown in Appendix A. Total precipitation during the 2021 and 2022 growing seasons measured 444–451 and 295–327 mm, respectively, with 2021 precipitation substantially higher than 2022, primarily attributable to July rainfall variations. The average air temperature during the rice growth period reached 18.7°C–19.9°C in 2021, while 2022 temperatures averaged 19.0°C–20.6°C.

### 2.2. Experimental treatments and procedures

Five rice production patterns were evaluated using three replications in 2021 and 2022: (1) Continuous flooding with mulch film (MCF). Fields were flood-irrigated by maintaining a 0–1 cm water layer above the biodegradable film from transplanting to two weeks before harvest. (2) Controlled irrigation with mulch film (MCI). The field water remained above the biodegradable film for one week after transplanting, then maintained in ditches between raised beds until two weeks before harvest. (3) Continuous flooding (CF), the traditional rice irrigation method in Northeast China. Fields were flood-irrigated by maintaining a 3–5 cm water layer above the soil surface from transplanting to two weeks before harvest. (4) Drip irrigation with mulch film (MDI). Post-sowing irrigation maintained 100% field capacity using a drip irrigation biodegradable mulch film system when soil moisture (0–40 cm depth) fell below 60% of field capacity during the milk-ripe stage and below 70% during other growth stages. (5) Drip irrigation without mulch film (DI), managed identically to MDI treatment except without biodegradable mulch film (Appendix B). Biodegradable film (PBAT) mulch of 8 μm thickness and 1.5 m width was utilized for all mulching methods. The treatments showed varying degradation rates, with MCF degrading first and MDI last (Appendix C). Each 9.9 m×10 m plot was separated by waterproofing membrane (0.35 mm thickness, 0.9 m depth) to prevent lateral seepage.

The study used Baonong 5 (*Oryza sativa* L. subsp. *japonica* Kato) single-crop rice variety. In paddy fields (MCF, MCI, and CF treatments), rice transplantation occurred on May 21, with harvests on September 20, 2021, and September 18, 2022. In drip-irrigated fields (MDI and DI

treatments), sowing took place on April 27, with harvests on September 20, 2021, and September 25, 2022. Mechanical transplanting employed row and intra-row spacing of 30 and 14 cm for MCF, MCI, and CF plots, respectively, averaging five seedlings per hole. Five rice rows were planted on one film layer in MCF and MCI plots. The plots of MDI and DI were utilized for direct-seeding under drip-irrigation at 3 cm depth, averaging 12 grains per hole. Eight rice rows were planted on one film layer using dual drip irrigation tapes with row spacing of 15–10–25–10–30–10–25–10–15 cm and plant spacing of 10 cm (Appendix D). Film spacing measured 15 cm in MCF, MCI, and MDI treatments. Ditch depth between raised beds in MCI treatment was 10 cm. Irrigation system specifications appear in Gao *et al.* (2023a). The five rice production systems' irrigation details are presented in Appendix E. Field practices including fertilizer management, pest control, and fallow followed local agronomic protocols (Gao *et al.* 2023a).

### 2.3. Sampling, measurement and analyses

Soil temperature measurements were conducted using a geothermometer which was installed in the soil prior to rice sowing or transplanting, positioned in the plot rows at depths of 5, 15, and 25 cm in Appendix D, with 1 h recording intervals and three replications. Soil moisture content was determined using the "oven drying method" with three replications per treatment (Gu *et al.* 2021). Soil samples were collected manually from each plot in the same row using a 70 mm diameter portable auger in Appendix D. Given the frequent irrigation during the rice reproductive period, sampling began 1–2 d before planting or transplanting, followed by weekly sampling at depths of 0–20 cm. The soil water content (%) was determined from soil samples dried at 105°C.

Four representative rice hills were selected from each plot at the max-tillering (MT), panicle initiation (PI), and grain maturity (GM) stages of rice. Root samples were extracted from the plant center in a vertical direction across a 40 cm area (four layers at 0–20 cm soil depth and two layers at 20–40 cm soil depth). Root augers of 14 cm diameter were utilized for the MCF, MCI, and CF treatments, while 10 cm diameter borers were used for the MDI and DI treatments. The collected root samples were placed in mesh bags with 0.5 mm hole diameter, soaked for 24 h, and cleaned with a high-pressure water gun (Wang *et al.* 2016). Subsequently, the samples were transported to the laboratory, where visible root samples were carefully selected using tweezers, scanned with a scanner (Epson V800, Japan), and analyzed to obtain root trait data and calculate root length and surface area using WinRHIZO software (version 5.0). The aboveground and root samples were then dried at 105°C and subsequently at a constant temperature of 75°C to determine dry matter weight.

At harvest, eight representative rice hills were selected from each plot to measure tiller numbers and plant height, while leaf area parameters were obtained using a Li-3100 scanner (Li-COR Inc., Lincoln, NE, USA). Subsequently, all sample plots covering 16.5 $m^2$ within the plots were harvested, naturally dried, and assessed for grain yield (14% moisture content). Water productivity (WP, kg $m^{-3}$) was calculated as: WP=Grain yield (kg $m^{-2}$)/(Precipitation+Irrigation) (mm)×10.

### 2.4. Statistical analyses

Statistical analyses were performed using SPSS software (version 19.0, SPSS Inc., Chicago, USA) for ANOVA tests and regression analysis. Origin 2021 was used for figure generation. Data normality was assessed using the Shapiro-Wilk test ($P$<0.05), which is appropriate for small to moderate sample sizes. Homogeneity of variance was evaluated using Levene's test prior to ANOVA analysis. Multiple comparisons of means were conducted using Tukey's $HSD_{0.05}$ test. A mixed model incorporating a compound symmetry (CS) covariance structure evaluated interactions between years and variables. The year was treated as a random factor in the mixed model to account for interannual variability and enhance result generalizability, with significance determined using the Likelihood Ratio Test (LRT). Regression analysis examined relationships among grain yield, water productivity, root biomass and traits at different growth stages, and soil temperature across rice production systems ($^{*}$, $P$<0.05 and $^{**}$, $P$<0.01).

## 3. Results

### 3.1. Soil temperature andwater contents

Soil temperature patterns remained consistent at various depths during the two-year rice growth period (Fig. 1). The soil temperature increase with biodegradable mulch film was notable primarily during the early rice growth stage ($P$<0.05), diminishing or disappearing in later stages as the biodegradable film degraded and plants developed. At 5 cm soil depth, MCF and MCI treatments elevated daily soil temperature by 0.8 and 4.6%, respectively, compared to CF treatment. At 15 cm, increases were 0.5 and 3.8%, and at 25 cm, 0.1 and 3.2%. The MDI treatment increased soil temperatures by 3.4, 2.5, and 1.4% at depths of 5, 15, and 25 cm, respectively, compared to DI treatment. Additionally, MCF and MCI treatments increased cumulative soil temperature in the tillage layer by 9 and 102°C over CF treatment, while MDI showed an 80°C increase over DI treatment.

The soil water content at 0–20 cm depth was consistently higher in the rice transplanting system compared to the rice direct dryland seeding system throughout the two-year growing period (Fig. 2). Surface soil moisture exhibited greater fluctuation in the MCI treatments, ranging from 19.8 to 32.9%, while in the MDI treatments, fluctuations were comparable to the DI treatments, ranging from 11.8 to 26.6%. The MCF and CF treatments maintained flooding conditions in the 0–20 cm soil layer and received no irrigation except during the two weeks preceding harvest. Consequently, these treatments showed no variations in soil water content.

### 3.2. Morphology distribution of rice root systems

The rice root system was instrumental in determining soil water and nutrient acquisition. Root length density (RLD), root weight density (RWD), and root surface area density (RSD) were analyzed at various soil depths across five rice

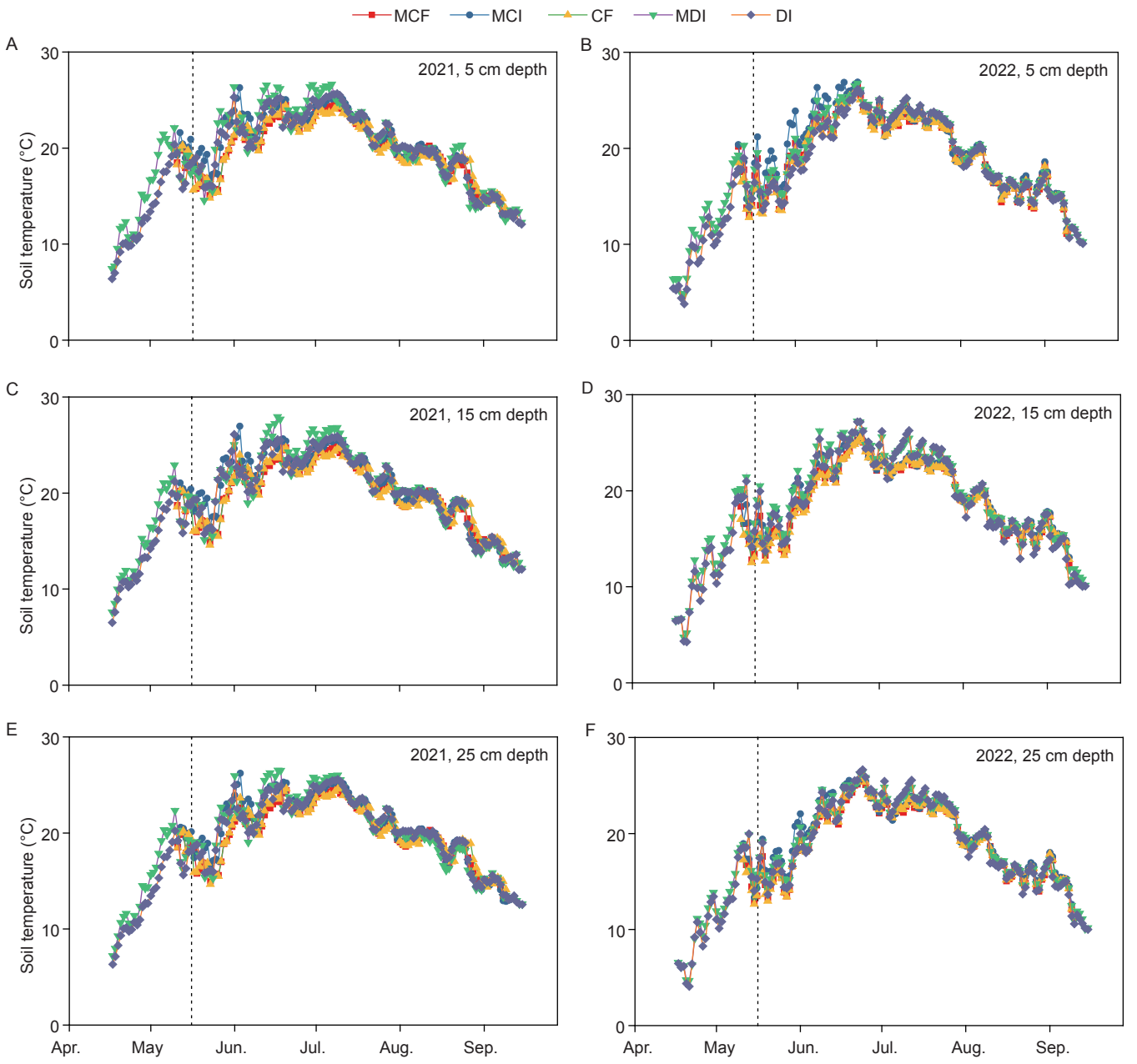



**Fig. 1 Temporal variations in average soil temperature throughout the soil profile during the rice growing season, as influenced by biodegradable mulch film under five distinct water management regimes in rice cultivation systems at Jalaid Banner, Inner Mongolia, Northeast China.** MCF, continuous flooding with biodegradable mulch film; MCI, controlled irrigation with biodegradable mulch film; CF, continuous flooding; MDI, drip irrigation with biodegradable mulch film; DI, drip irrigation without mulch film. Regression analyses revealed significant correlations among all treatments until mid-May ($P$<0.05).

production patterns over two years (Figs. 3–5). The majority of crop roots were concentrated in the 0–10 cm soil layer, with density decreasing substantially as depth increased. The 0–10 cm soil layer contained more than 65% of roots, while the 0–20 cm layer contained 85%. Analysis of RLD, RWD, and RSD in the uppermost 0–10 cm soil profile at the MT stage revealed substantial differences between the two cropping systems based on mulching practices. Additionally, total RWD demonstrated significant positive correlations with both total RLD and total RSD across all growth stages ($P$<0.05) (Fig. 6).

During 2021–2022, rice RLD showed an increasing trend from MT to PI at 0–40 cm soil depth, followed by a gradual decline toward GM (Fig. 3). In the rice transplanting system, the total RLD of MCF and MCI treatments increased by an average of 29.4% compared to the CF treatment at MT stage, though no significant differences were observed thereafter. In the rice direct dryland seeding system, the MDI treatment exhibited significantly higher total RLD than the DI treatment by 42.9% (MT stage), 24.8% (PI stage), and 19.2% (GM stage), respectively ($P$<0.05).

Throughout both study years, rice RWD gradually increased from MT to GM stages at 0–40 cm soil profile depth (Fig. 4). In the rice transplanting system, the total RWD of

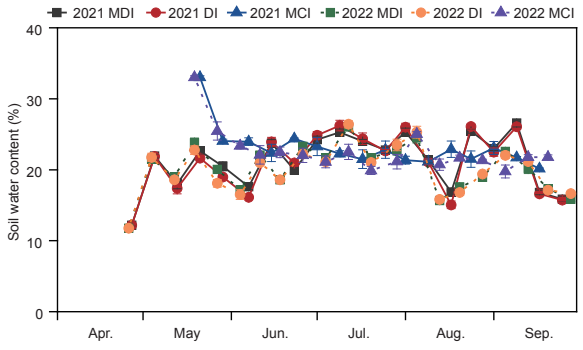



**Fig. 2 Temporal variations in mean soil water content at 0–20 cm soil depth during rice growth periods in 2021 and 2022 across different rice production systems.** MDI, drip irrigation with biodegradable mulch film; DI, drip irrigation without mulch film; MCI, controlled irrigation with biodegradable mulch film.

MCF and MCI treatments increased by an average of 27.2% compared to the CF treatment at MT stage, with no significant differences between MCF and MCI treatments throughout the growth period. The MDI treatment demonstrated significantly higher total RWD ($P$<0.05) than the DI treatment in rice direct dryland seeding system by 14.8% (MT stage), 17.5% (PI stage), and 13.1% (GM stage), respectively. The MDI and DI treatments exhibited similar RWD changes at soil depths of 0–10 and 10–20 cm.

During 2021–2022, all treatments displayed similar trends in RSD and RLD from MT to PI and GM stages (Fig. 5). In the rice transplanting system, the total RSD of MCF and MCI treatments exceeded that of the CF treatment by an average of 17.7% throughout the growth period ($P$<0.05). Similarly, in the rice direct dryland seeding system, the MDI treatment showed significantly higher total RSD than the DI treatment by 33.3% ($P$<0.05).

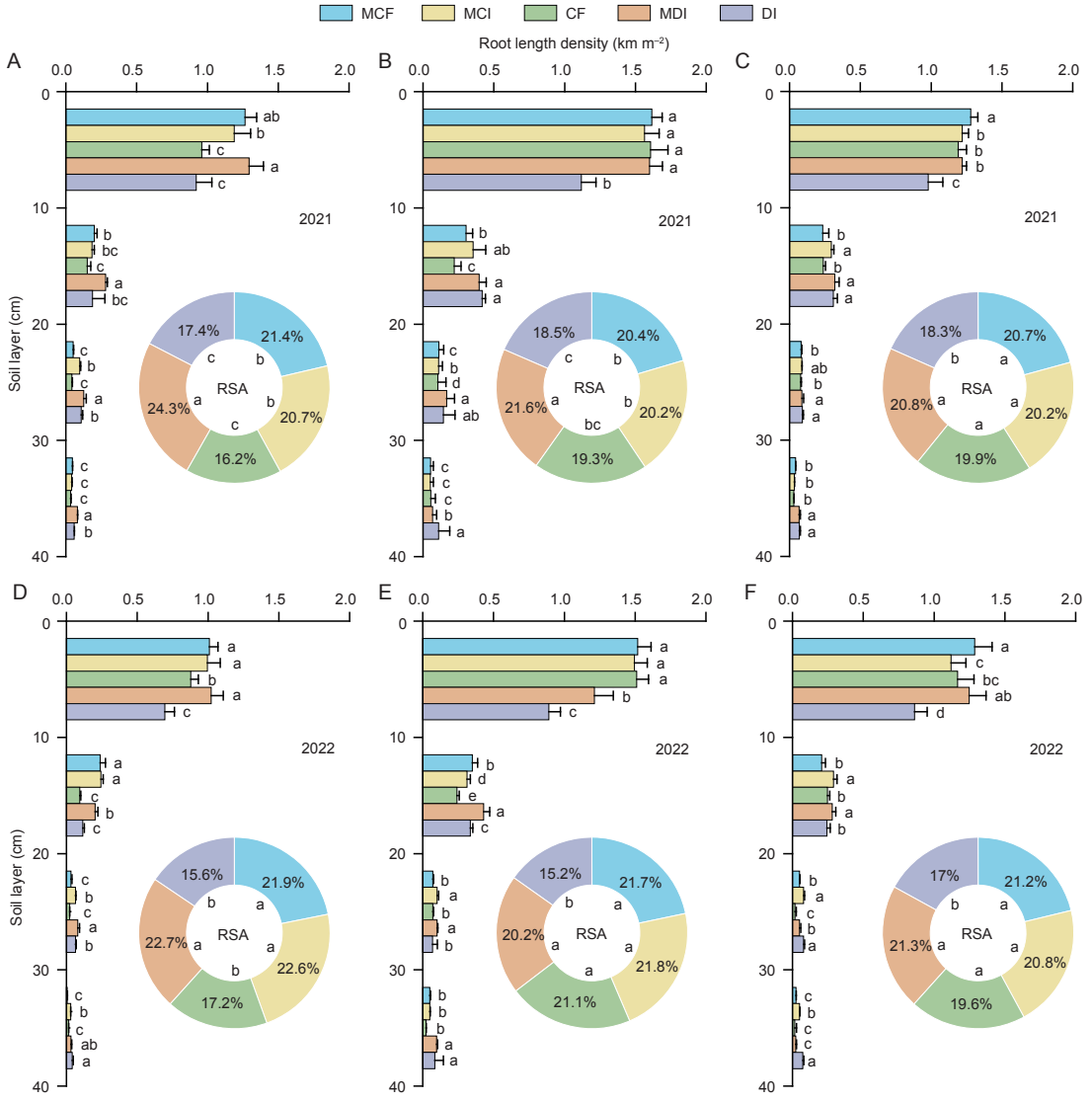



**Fig. 3 Effects of five rice production systems on root length density distribution across soil depths at max-tillering (A and D), panicle initiation (B and E), and grain maturity (C and F) stages in 2021 and 2022.** The ring statistics analyses (RSA) indicate the percentage of total root length density at 0–40 cm soil depth for each treatment in 2021 and 2022. MCF, continuous flooding with biodegradable mulch film; MCI, controlled irrigation with biodegradable mulch film; CF, continuous flooding; MDI, drip irrigation with biodegradable mulch film; DI, drip irrigation without mulch film. Values represent mean±SD ($n$=3). Different lowercase letters indicate significant differences at the 0.05 level among treatments.

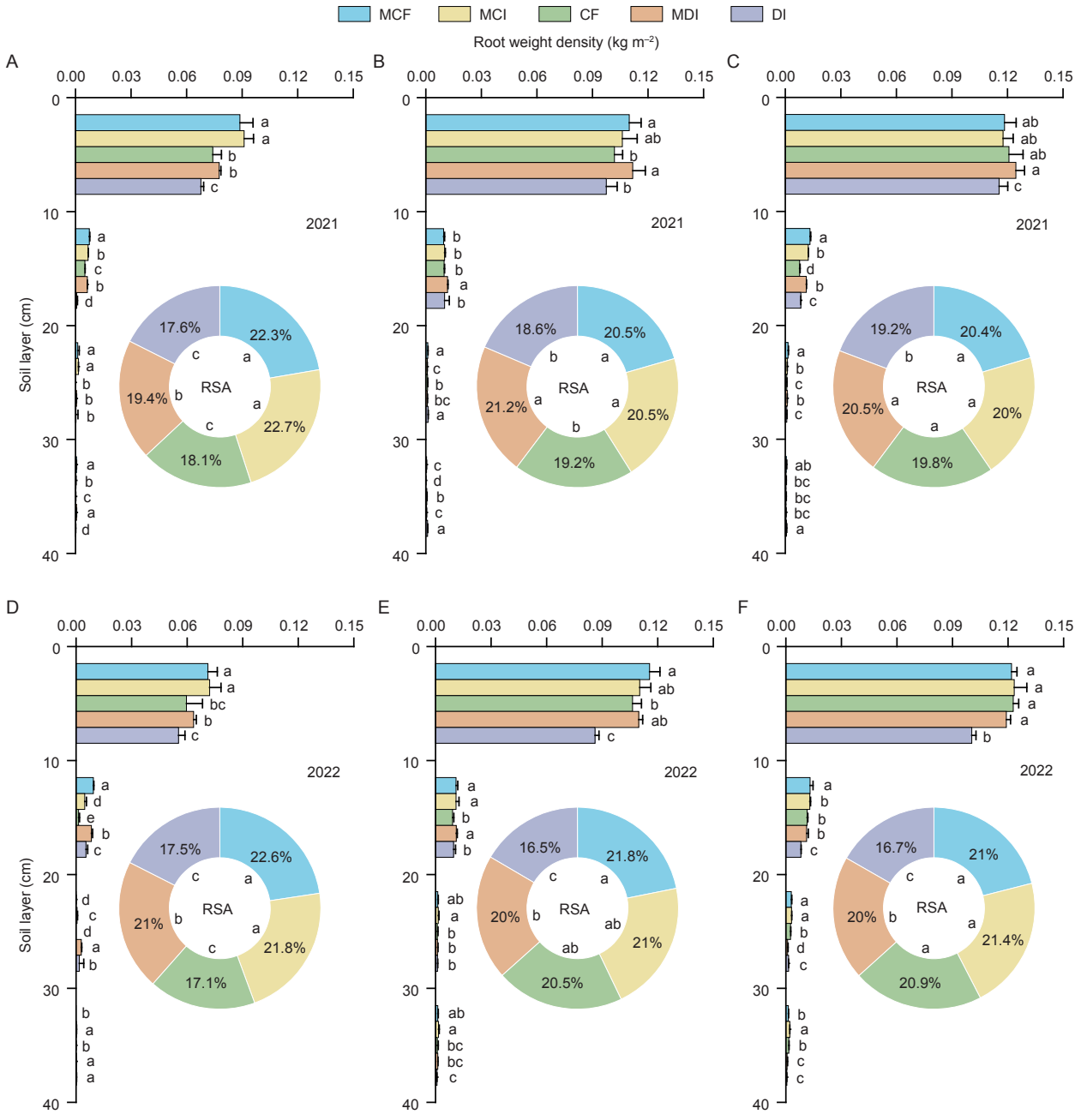



**Fig. 4 Influence of five rice production systems on root weight density distribution across soil depths at max-tillering (A and D), panicle initiation (B and E), and grain maturity (C and F) stages during 2021 and 2022.** The RSA indicate the percentage distribution of total root weight density within 0–40 cm soil depth for various treatments in 2021 and 2022. MCF, continuous flooding with biodegradable mulch film; MCI, controlled irrigation with biodegradable mulch film; CF, continuous flooding; MDI, drip irrigation with biodegradable mulch film; DI, drip irrigation without mulch film. Values represent mean±SD ($n$=3). Different lowercase letters indicate significant differences at the 0.05 level among treatments.

### 3.3. Rice yield, water productivity, and net profit

Biodegradable mulch film significantly enhanced rice grain yield and WP in 2021 and 2022 ($P$<0.05). Relative to CF treatment, MCF treatment enhanced yield and WP by 17.2 and 34.9%, MCI treatment increased yield and WP by 10.0 and 39.6%, while MDI and DI treatments improved WP by 60.9 and 14.4%, respectively. Additionally, no significant differences were observed between MDI and CF treatments regarding yield, or between MCF and MCI treatments regarding WP. The yield of the DI treatment, however, was 19.6% lower than the CF treatment (Fig. 7). Among the five rice production patterns, MCI treatment exhibited the highest total costs at 21,185 CNY ha$^{-1}$ (Appendix F), primarily attributed to biodegradable film procurement and soil preparation costs. Nevertheless, MCF treatment generated the highest net profits at 11,783 CNY ha$^{-1}$.

At harvest, biodegradable mulch film significantly enhanced plant height and shoot dry matter in the rice direct dryland seeding system across all years ($P$<0.05). The root/shoot ratios for CF treatment exceeded those of

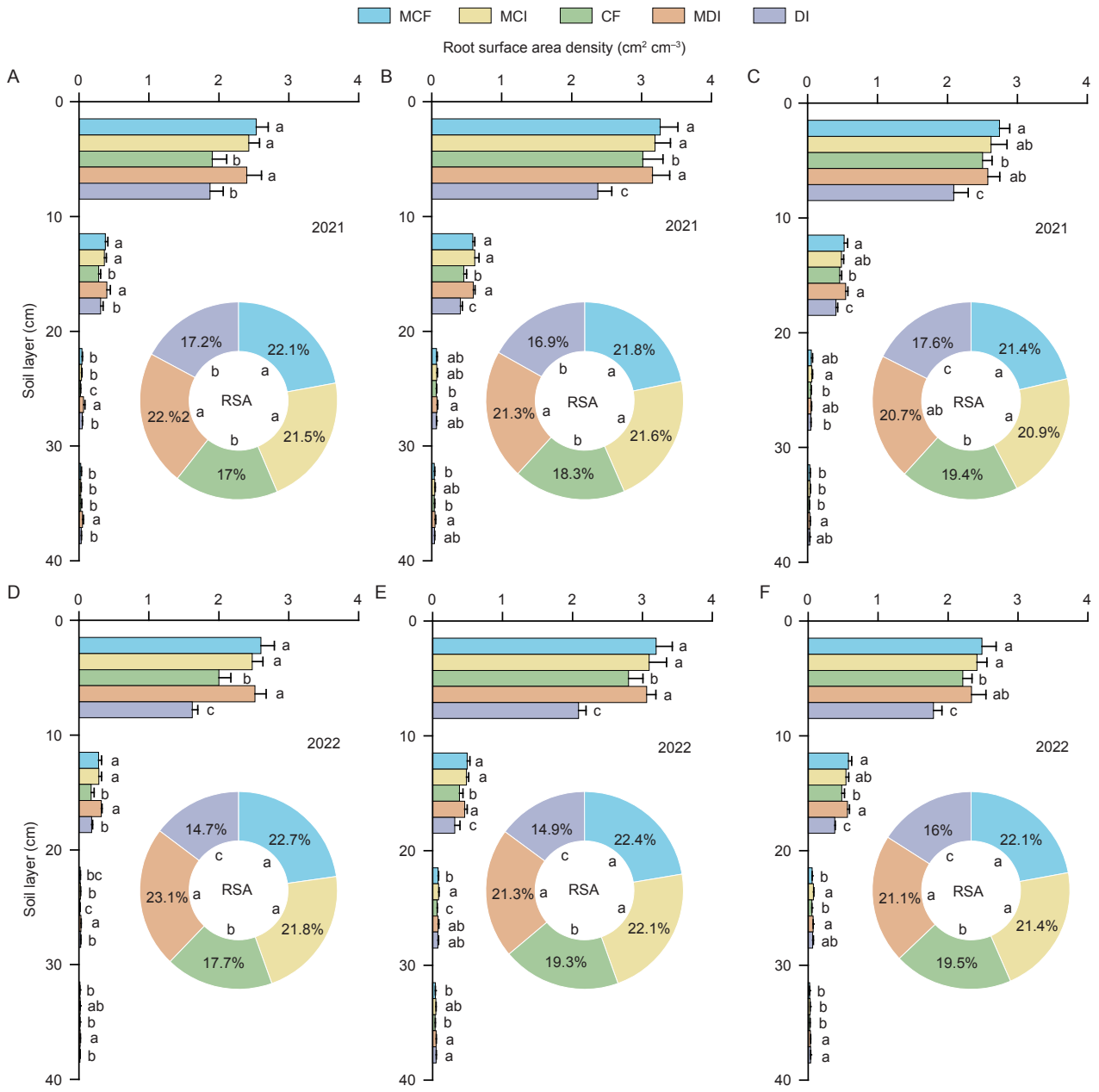



**Fig. 5 Effects of five rice production systems on root surface area density distribution across soil depths at max-tillering (A and D), panicle initiation (B and E), and grain maturity (C and F) stages in 2021 and 2022.** The RSA indicate the percentage of total root surface area density at 0–40 cm soil depth for different treatments in 2021 and 2022. MCF, continuous flooding with biodegradable mulch film; MCI, controlled irrigation with biodegradable mulch film; CF, continuous flooding; MDI, drip irrigation with biodegradable mulch film; DI, drip irrigation without mulch film. Values represent mean±SD ($n$=3). Different lowercase letters indicate significant differences at the 0.05 level between treatments.

MCF and MCI treatments. No significant differences were observed between biodegradable mulch film and no mulching treatments in tiller number and leaf area index (Appendix G). Analysis of data across all growth stages revealed significant positive correlations between root characteristics (RLD, RWD, and RSD) and grain yield, WP, and shoot dry matter (Fig. 8).

## 4. Discussion

### 4.1. Soil temperature and water content in different rice production patterns

Biodegradable mulch film enhances precipitation utilization and maintains soil moisture content, while increasing soil temperature (Nelson *et al.* 2020; Qian *et al.* 2023). Compared to traditional flooding cultivation, biodegradable mulch film demonstrates effectiveness in water-saving rice production by elevating soil temperature and conserving soil moisture through several mechanisms (Figs. 1 and 2): Mulching improves field water absorption while reducing heat exchange between soil and atmosphere, thus decreasing latent heat exchange losses and increasing soil heat flux and temperature (Gu *et al.* 2017). The biodegradable film restricts matter and energy exchange between the paddy field and external environment, allowing water vapor evaporated

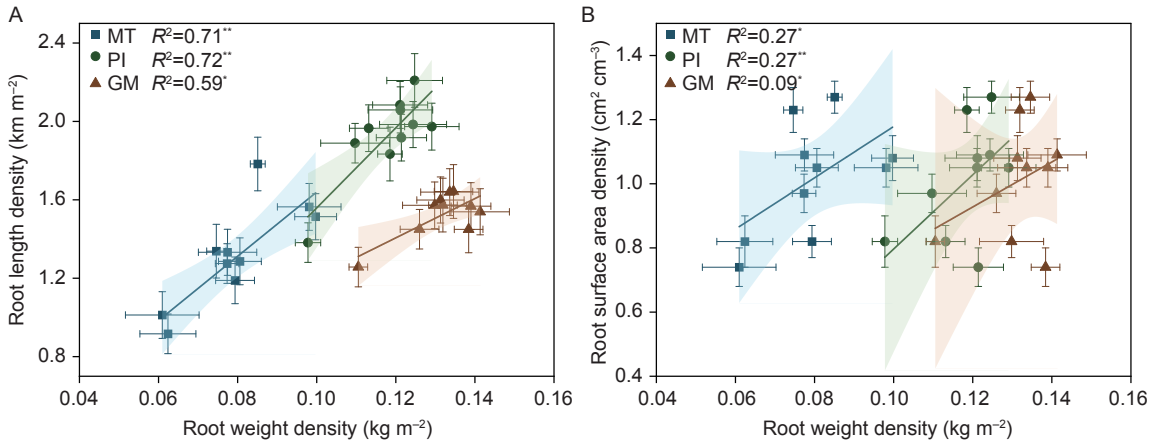



**Fig. 6 Correlations between root weight density and root length density (A), and root surface area density (B) at max-tillering (MT), panicle initiation (PI), and grain maturity (GM) stages.** Values represent mean±SD ($n$=3). * and ** represent significance at $P$<0.05 and $P$<0.01, respectively.

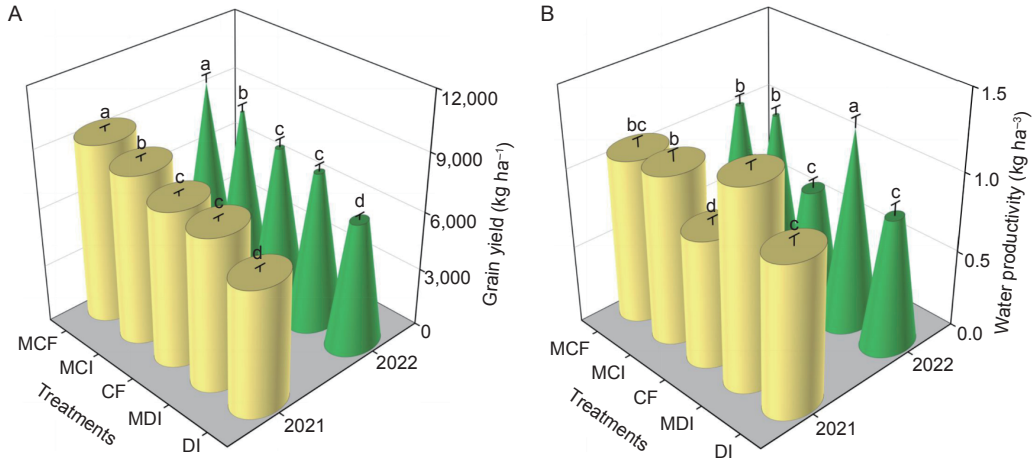



**Fig. 7 Grain yield (A) and water productivity (B) across five rice production systems in 2021 and 2022.** MCF, continuous flooding with biodegradable mulch film; MCI, controlled irrigation with biodegradable mulch film; CF, continuous flooding; MDI, drip irrigation with biodegradable mulch film; DI, drip irrigation without mulch film. Values represent mean±SD ($n$=3). Different lowercase letters indicate significant differences at the 0.05 level between treatments.

from the soil to remain in the air chamber between field and film (You *et al.* 2021). Temperature reduction triggers vapor condensation into droplets, which return to the soil, enhancing soil water storage and moisture retention (Huang *et al.* 2022).

In this study, the soil warming effect of different mulching and planting methods gradually diminished with increasing soil depth or growth progression, aligning with previous research findings (Gu *et al.* 2017, 2020). Furthermore, biodegradable mulch film exhibited varying effects on soil warming and moisture maintenance across different cropping systems throughout the growth period (Fig. 1). This variation may be attributed to differences in mulching timing between systems (early May in rice transplanting system *vs*. early April in rice direct dryland seeding system) and varying degradation rates of biodegradable film under distinct ecological conditions (Yin *et al.* 2019; Sintim *et al.* 2020; Bianchini *et al.* 2022). The effects of biodegradable mulch film on soil conditions differed markedly between paddy and typical dryland crops, such as maize (Shangguan *et al.* 2024). Unlike dryland maize systems, where biodegradable film primarily reduces evaporative water loss, rice systems benefited from both temperature moderation and water conservation, resulting from the combined effects of flooding and biodegradable mulch film.

### 4.2. The benefit of biodegradable mulch film on root systems

Rice root growth and development demonstrate strong correlations with production patterns and soil environments (Hasegawa *et al.* 2021; Wang *et al.* 2021). This study demonstrates that biodegradable mulch film enhances total RLD, RWD, and RSD during early growth stages in water-saving rice production (Figs. 3–5). While root system development experiences inhibition during later growth periods in the rice transplanting system, it maintains superiority over non-mulching treatment in the rice direct dryland seeding system. This advantage primarily stems from intact biodegradable film maintaining stable soil moisture and

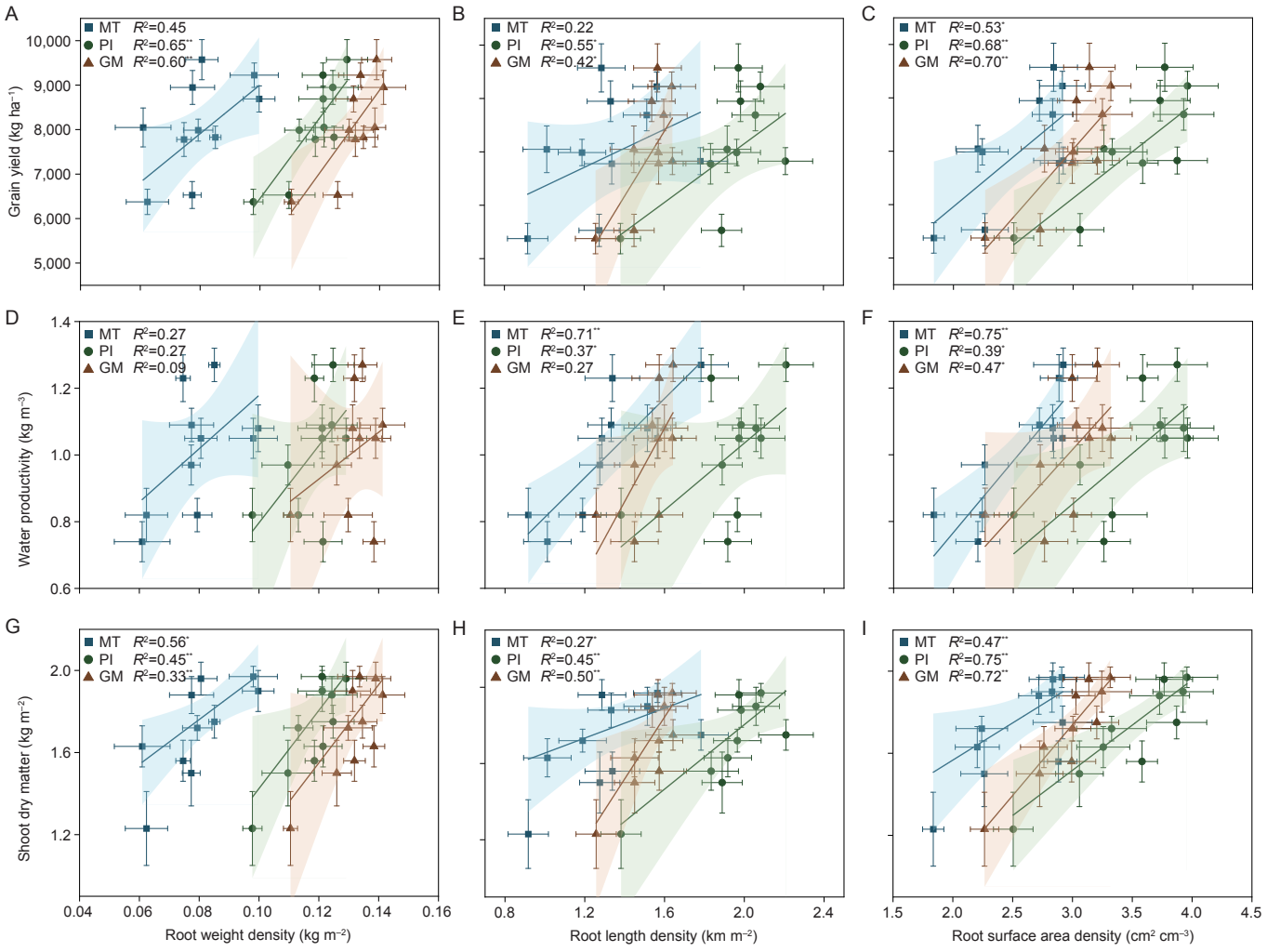



**Fig. 8 Analysis of grain yield, water productivity, and shoot dry matter in relation to root characteristics (0–40 cm) at max-tillering (MT) stage, panicle initiation (PI) stage, and grain maturity (GM) across five rice production systems.** Values represent mean±SD ($n$=3). * and ** represent significance at $P$<0.05 and $P$<0.01, respectively.

temperature for 40 to 60 days post-application (Appendix C), creating optimal soil conditions for root growth in the 0–20 cm soil layer. Additionally, biodegradable mulch film facilitates the translocation of assimilates from aboveground to belowground in water-saving rice production (Zhang *et al.* 2017b). Root growth experiences subsequent inhibition as the film degrades and its warming effect diminishes, coupled with declining soil fertility (Wang *et al.* 2019). Despite faster degradation of biodegradable film in MCF treatment compared to MCI treatment, soil moisture remains saturated under MCF treatment, allowing continued root development benefit from rising temperatures. The MDI treatment exhibits the lowest degradation rate, entering the cracking period after 77 days (Appendix C). At this stage, RLD, RWD, and RSD demonstrate robust development, surpassing non-mulching treatment performance even under late-stage water stress.

Significant positive correlations between total RWD and total RLD or total RSD at each growth stage indicate root system health and integrity (Tao *et al.* 2015). Approximately 85% of the total RLD, RWD, and RSD in each treatment concentrates in the 0–20 cm soil layer, with decreasing values at greater depths (Figs. 3–5). MCI, MDI, and DI treatments exhibit greater total root length in deeper soil layers compared to the CF treatment (Fig. 3). This observation aligns with the theory that reduced water utilization promotes root development (Zhang *et al.* 2022), resulting in deeper rice rooting for enhanced water absorption (Yang *et al.* 2012). Furthermore, the roots increase their soil contact area, enabling greater water and nutrient uptake for plant growth and development.

### 4.3. Biodegradable mulch film improved productivity and sustainability by enhancing root systems

Enhanced root system development plays a crucial role in improving crop productivity and sustainability (Ontl *et al.* 2013; Singh *et al.* 2019). Increased RLD, RWD, and RSD enhance the crop's capacity to absorb soil water and nutrients, improving adaptation to drought conditions caused by global warming (Gao *et al.* 2021). Additionally, stronger and deeper root systems under biodegradable mulch film reduce lodging risk (Zhang *et al.* 2023). This study reveals positive correlations between root characteristics (RLD, RWD,

and RSD) and grain yield, WP, and shoot dry matter (Fig. 8). These findings align with previous studies demonstrating root development's contribution to crop production through enhanced root system elongation and branching (Hakl *et al.* 2017; Gomes *et al.* 2019; Zheng *et al.* 2021). Consequently, increased root biomass in the 0–40 soil layer under mulching enhances aboveground biomass accumulation compared to no-mulch treatment (Fig. 4). Furthermore, biodegradable mulch film enhances assimilate allocation efficiency to yield at appropriate irrigation levels (Wang *et al.* 2021). Thus, MCF, MCI, and MDI treatments increase yield, net profit, and WP in both rice transplanting and direct dryland seeding systems.

## 5. Conclusion

This study aimed to investigate the effects of biodegradable mulch film on soil temperature, moisture content, and root growth distribution at various soil depths, while analyzing the relationships between root characteristics, grain yield, and water productivity in water-saving plastic mulch rice production systems. The research demonstrated that biodegradable mulch film significantly enhanced soil temperature and moisture retention, particularly during early growth stages in water-saving rice production. These production patterns could effectively mitigate low spring temperature stress and water scarcity challenges in Northeast China. Furthermore, biodegradable mulch film substantially improved RLD, RWD, and RSD in water-saving rice production compared to non-mulching controls. The enhancement of these root characteristics at a soil depth of 0–40 cm throughout all stages contributed significantly to increased rice yields (10.0–17.2%), improved water productivity (35.0–40.5%), and enhanced shoot dry matter under water-saving plastic mulch rice production systems. Among the treatments evaluated, MCF achieved optimal rice yield and net profit, while MDI treatment demonstrated superior water productivity. The findings indicate that enhanced root morphology characteristics played a crucial role in improving yields and system sustainability through the application of biodegradable mulch film in water-saving rice production.

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## Declaration of competing interest

The authors declare that they have no conflict of interest.

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

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

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