EFFECT OF CONTROLLED-RELEASE FERTILIZER ON MAIZE YIELD AND NUTRIENT UPTAKE UNDER A FERTILIZER ONE-TIME POINT-APPLIED SYSTEM
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一次性机械化穴施缓释复合肥对玉米产量和养分吸收的影响

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DOI: https://doi.org/10.35633/inmateh-69-65

Keywords: *Maize; Nutrient uptake; Fertilizer; Fertilizer point-applied*

ABSTRACT
Currently, maize production in China suffers from many problems, such as excessive fertilizer application, inefficient fertilizer use, and insufficient agricultural labour. The effect of one-time mechanical point-applied fertilization of controlled-release compound fertilizer in the root-zone on yield and nutrient uptake was investigated to explore efficient fertilization patterns for fertilizer decrease and yield increase in maize. The selected fertilizer was a controlled-release granular fertilizer (24-6-10 for N-P_2O_5-K_2O) with six treatments in the application program: 1) no fertilizer (CK); 2) application of a one-time banding fertilizer (BDP) 5 cm off the seeds between rows and 10 cm deep; 3) application of a one-time point-applied fertilization (RZF) 5 cm off seed in the row and 10 cm deep; 4) application of a one-time point-applied fertilization (90% RZF) 10% fertilizer reduction 5 cm off seed in the row and 10 cm deep; 5) application of a one-time point-applied fertilization (80% RZF) 20% fertilizer reduction 5 cm off seed in the row and 10 cm deep; 6) application of a one-time point-applied fertilization (70% RZF) 30% fertilizer reduction 5 cm off seed in the row and 10 cm deep. The results showed that RZF increased yield by 5.84% over BDP, and the difference was significant, indicating that mechanized point-applied fertilization of fertilizer can replace manual point-applied fertilization application operations and achieve increased crop yield. The agronomic utilization rate of fertilizer of 12.35% and the bias productivity of 5.31% were higher in RZF than in BDP, and the differences were significant, indicating that one-time mechanical point-applied fertilization in the root zone significantly improved fertilizer utilization and reduced fertilizer loss.

摘要
针对夏玉米现有施肥模式下施肥量大、肥效低导致面源污染大、单产低的问题，通过研究根区一次性机械化穴施缓释复合肥对夏玉米产量和养分吸收的影响，探索减肥增产的玉米高效施肥模式。选用肥料为缓释颗粒肥（N-P_2O_5-K_2O 为 24-6-10），施肥方案共设 6 个处理，分别为：1）不施肥(CK)；2）行间偏离种子 5 cm、深 10 cm 一次性条施(BDP)；3）行间偏离种子 5 cm、深 10 cm 一次性穴施(RZF)；4）减肥 10%行间偏离种子 5 cm、深 10 cm 一次性穴施(90%RZF)；5）减肥 20%行间偏离种子 5 cm、深 10 cm 一次性穴施(80%RZF)；6）减肥 30%行间偏离种子 5 cm、深 10 cm 一次性穴施(70%RZF)。结果显示，根区一次性机械化穴施缓释复合肥（RZF）比一次性条施（BDP）增产 5.84%，且差异显著，说明机械化穴施肥料可以代替人工穴施肥作业，实现作物增产。RZF 的肥料农学利用率 12.35%、偏生产力 5.31%均比 BDP 高，且差异显著，说明根区一次性机械化穴施肥料显著提高了肥料利用率，减少了肥效损失和面源污染。RZF 与 BDP 相比，植株高度无显著差异，但植株茎粗、叶面积、伤流量和根系干物质量差异显著，说明根区施肥可促进根系生长，增大根长和根表面积，从而导致吸收水肥的能力更强，进一步表现为伤流量显著增大，从而提高地上部生长发育，增大叶面积，提高光合作用强度和碳水化合物的积累，实现籽粒增产。

INTRODUCTION
Maize (Zea mays L.) is one of the most widely grown crops in the world and ranks first for planting area and total production in China (*Hu et al.*, 2016). Maize is important for China's food production and food security (*MaCao*, 2021). Arable land in China is scarce, and the per capita area of arable land is approximately 0.1 ha and less than 40% of the world average (*Shan et al.*, 2021).

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Therefore, increasing maize productivity has become an important aspect to ensure food security (*Usman et al.*, 2021). However, to obtain high yields within short periods, growers often use large amounts of fertilizers, which cause fertilizer losses, waste resources and challenges to sustainable development of agricultural production (*Luan et al.*, 2020; *Ren et al.*, 2020; *Xu et al.*, 2019). Experts and scholars at home and abroad have done a lot of research to improve crop yields and fertilizer utilization (*Shi et al.*, 2020), but mostly focused on fertilizer varieties (*Anstoetz et al.*, 2015), dosage (*Wei et al.*, 2019) and fertilizer application locations (*Jiang et al.*, 2018), etc. Different fertilizer application methods directly affect the effectiveness of fertilizer and crop yield, and are the basis for achieving high crop yields and improving fertilizer efficiency.

The conventional fertilizer application mode applies fertilizer in a one-time banding fertilizer at a distance of 5~10 cm from the seed row and 10 cm deep at the time of maize sowing, and some conventional fast-acting fertilizers are in the soil far away from the roots with low root efficiency, so that the roots cannot absorb the nutrients released by the fertilizer particles in time, and the excess fertilizer nutrients leave the cultivated soil due to runoff, leaching or gaseous loss, thus causing groundwater or atmospheric pollution (*Ye et al.*, 2010; *Zhu*, 2013; *Chen et al.*, 1995). Recent studies have found that ammonia volatilization and runoff losses are significantly reduced when urea is point-applied to the root zone, greatly improving nitrogen fertilizer utilization (*Cao et al.*, 1984; *SavantDe Datta*, 1980). Wang (2013) believes that fertilizer application in the root zone ensures the best match between fertilizer and the active range of the root system, which in turn affects the migration and transformation of nutrients in the soil, the morphology and distribution characteristics of the root system, and thus acts on the uptake and transfer of nutrients to the above-ground parts of the crop to achieve a yield increase.

Zhou *et al.* (2020) found that a one-time root zone point-applied application under the monopoly furrow full film cover planting method was beneficial to nitrogen concentration of in the soil tillage layer, improving the efficiency of nitrogen utilization by summer maize and promoting dry matter accumulation and improving summer maize yield. Liu *et al.* (2017) found that by applying N fertilizer in the root zone of rice with a single point-applied, the apparent utilization rate of N fertilizer increased by 22.6%-30.6% and the loss of N decreased from 73.0% to 29.7% compared to the previous application, indicating that the application of N fertilizer in the root zone significantly increased the storage time of fertilizer nutrients in the soil and improved the efficiency of the utilization of N fertilizer in rice.

Chen *et al.* (2014) proposed a technique of simultaneous lateral deep fertilization of rice, and the results showed that the yield increase ranged from 5.86% to 13.41% compared with manual spreading of fertilizer. Jiang *et al.* (2018a; 2019; 2018b) studied the one-time root zone point-applied application of urea to maize than the one-time banding application of urea and farmers' customary split application of nitrogen increased yield by 9.8% and 8.8%, respectively, and the apparent utilization rate of nitrogen fertilizer increased by 12.4% and 8.3%, respectively, and found that the one-time root zone point-applied application of urea can achieve the effect of slow and controlled release fertilizer and improve the utilization rate of nitrogen fertilizer.

Zhang *et al.* (2020) used an indoor simulation experiment to study the nutrient transport pattern of nitrogen, phosphorus and potassium under the point-applied application of urea, ammonium polyphosphate and potassium chloride compound fertilizers, and found that the nitrification of ammonium nitrogen under fertilizer point-applied application conditions was inhibited by the high concentration of nutrients between fertilizers, thus delaying the conversion of ammonium nitrogen to nitrate nitrogen, which was an important reason for the continuous and efficient supply of nitrogen fertilizer in the root zone primary application technique. Guo *et al.* (2020) showed that full inter-plant point-applied application increased plant yield by 3.70%, biomass above-ground by 3.56%, and the accumulation of N and P nutrients by 11.24% and 19.44% compared to the open-row strip application.

From the above studies, it can be seen that most of the research reports on point-applied application of fertilizers in the root zone are on manual application of a single fast-acting fertilizer, focusing on basic research on the mechanism of fertilizer transport, dynamic diffusion and migration patterns of nutrients, and spatial and temporal distribution characteristics of root morphology. Little research has been reported on the interactions between the soil, machine and plant on maize yield and the efficiency of nutrient system. Based on the point-applied fertilization planter for maize developed by the project team (*Du et al.*, 2022), this paper investigated the effects of one-time mechanical application of slow-release compound fertilizer on the yield and nutrient utilization efficiency of maize during the whole fertility period through two years of field trials, aiming to provide technical and theoretical support for fertilizer reduction and maize yield increase.

MATERIALS AND METHODS

Overview of the test field

The test site is located in XiaoDuzhuang Village, Shenze Town, Shenze County, Shijiazhuang City, Hebei Province, China, at 115°13'48.1" E longitude and 38°12'5.4" N latitude, with the average annual temperature of 12.4 °C, frost-free period of 188 days, average annual sunshine duration of 2714.1 hours, average annual rainfall of 489.8 mm, and temperate continental monsoon climate, with precipitation accounting for 54% of the annual precipitation during the test period (June-September). The previous crop was winter wheat, with a stubble height of 15-20 cm and a straw quantity of 0.66 kg/m^2. The soil of the test site was in the transition zone of tidal soil and brown soil, with a soil capacity of 1.37 g/cm^3 and a water content of 23.6%.

Experimental design

This study used the “Zhengdan 958” maize flat dentate hybrid produced by Henan Dacheng Seed Industry Co., Ltd. as the research object, with 60 cm spacing between rows and 25 cm spacing between plants, and single grain precision sowing. The selected fertilizer was a controlled-release granular fertilizer（24-6-10 for N-P_2O_5-K_2O）with six treatments in the application program: 1) no fertilizer (CK); 2) a one-time banding fertilizer application (BDP) 5 cm off the seeds between rows and 10 cm deep (735 kg/ha); 3) one-time point-applied fertilization (RZF) 5 cm off seed in the row and 10 cm deep (735 kg/ha); 4) one-time point-applied fertilization (90% RZF) 10% fertilizer reduction 5 cm off seed in the row and 10 cm deep (661.5 kg/ha); 5) one-time point-applied fertilization (80% RZF) 20% fertilizer reduction 5 cm off seed in the row and 10 cm deep (588 kg/ha); 6) one-time point-applied fertilization (70% RZF) 30% fertilizer reduction 5 cm off seed in the row and 10 cm deep (514.5 kg/ha).

The plot size was 2.4 m × 25 m (4 row zones, 100 plants per row, 400 plants in total), with 3 replications and randomized group arrangement. Field management measures such as pest and weed control and irrigation were consistent among different treatments. The field trial period was from June to September of 2020 and 2021, respectively.

Measurement items and methods

Collection and determination of plant samples

Five plants for each repetition were randomly selected to measure plant height and stalk diameter (diameter of maize stalk base) at the elongation, flared, spanning and grouting stages, respectively; five plants were randomly selected to measure plant leaf area at the cob position (single leaf area = leaf length × leaf width × 0.75) at the flared, spanning and grouting stages, respectively.

Collection and determination of soil samples

Root system determination: Five plants for each repetition were randomly selected at the spanning stage of maize, and the soil was dug out with a 30 cm radius and 30 cm depth, the soil was rinsed off with water, and the roots were dried at 80°C for 12 h and weighed for dry weight.

Determination of root injury flow: 5 plants for each repetition were randomly selected at the flared, spanning and grouting stage, respectively. At 18:00, cut the stalk horizontally with a sharp blade from a height of 10 cm above the ground and keep the incision flat, quickly put on the pre-prepared wound fluid collection bag, and fasten it with a cable tie. The collection belt is an intact transparent sealed bag with dry absorbent cotton inside. Weigh before use (W_1) and make a label, collect for 12 hours (the wound fluid should not exceed the saturated absorption capacity of absorbent cotton), remove the collection bag, and weigh again (W_2) to obtain the root wound flow $W = W_2 - W_1$.

Production and seed counting

After maturity, maize ears were harvested from the whole plot of each treatment, and the number of harvested ears was calculated and the average number of grains per ear was determined. The 1000-grain weight is based on the average 1000-grain weight of the tested varieties in the past three years. The final grain yield is 85% of the product of the number of ears per hectare, the number of grains per ear and the 1000-grain weight.

Calculation of relevant indicators and statistical methods

Agronomy efficiency (AE, kg/kg) = [yield in fertilized area (kg/ha)- yield in the control area (kg/ha)]/ nutrient application (kg/ha)

Partial factor productivity (PFP, kg/kg) = yield (kg/ha) / nutrient application (kg/ha)

SPSS 19.0 software was used for variance analysis, and Duncan's new multiple range method was used to judge the significant difference between treatments ($P<0.05$), and Origin2018 software was used to draw.

RESULTS

Effect of different fertilizer application methods on maize plant height and stalk diameter

It can be seen from Figure 1 that, compared with CK, the one-time mechanized fertilization in the root zone increased the plant height by 26.77%-36.67%. At the elongation stage, the maize plant height of BDP was slightly higher than that of RZF, and the plant height decreased gradually with the decrease of fertilization amount. The plant height of RZF maize was slightly higher than that of BDP by 2.50%-4.03% at the flared, spanning and grouting stages, and the plant height of RZF gradually decreased by 6.66%-15.52% with the decrease of fertilization rate. There was no significant difference in maize plant height between BDP and RZF during the whole growth period, but RZF had higher plant height.

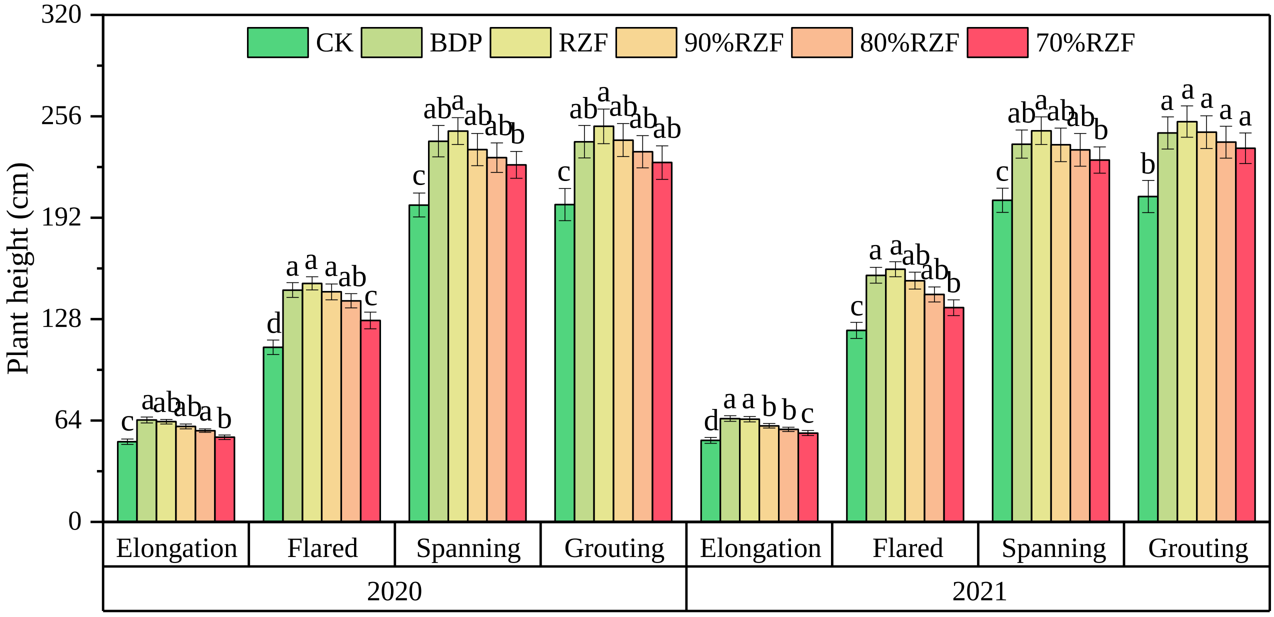

Fig. 1 – Effect of fertilizer application method on maize plant height

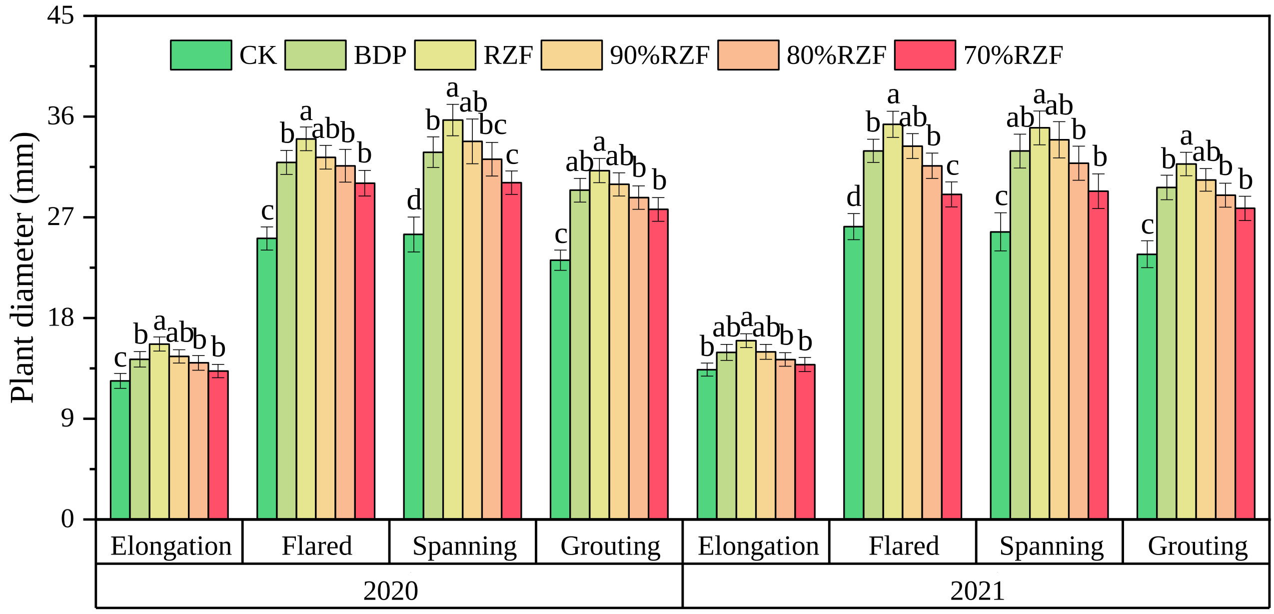

Fig. 2 – Effect of fertilizer application method on maize stalk diameter

As shown in Figure 2, compared with CK, one-time mechanized fertilization in the root zone increased stem diameter by 19.32%-40.17%. The stem diameter of RZF was 5.98%-9.54% larger than that of BDP at the elongation stage, flared stage, spanning stage and grouting stage, and the stem diameter of RZF plants decreased gradually by 11.14%-17.74% with the decrease of fertilization rate. The maize stalk diameter of RZF was significantly larger than that of BDP during the whole growth period.

Effect of different fertilizer application methods on maize leaf area

As can be seen from Figure 3, compared with CK, the one-time mechanized fertilization in the root zone increased the leaf area by 25.58%-32.56%, and the difference was significant. The maize leaf area of RZF was slightly higher than that of BDP by 6.63%-9.96% in the whole growth period, and the difference was significant. The leaf area of RZF plants decreased gradually by 12.10%-16.36% with the decrease of fertilization amount, and the difference was significant. There was no significant difference in maize leaf area between 90% RZF and BDP. RZF had the largest maize leaf area, indicating greater photosynthetic capacity and greater potential for yield increase.

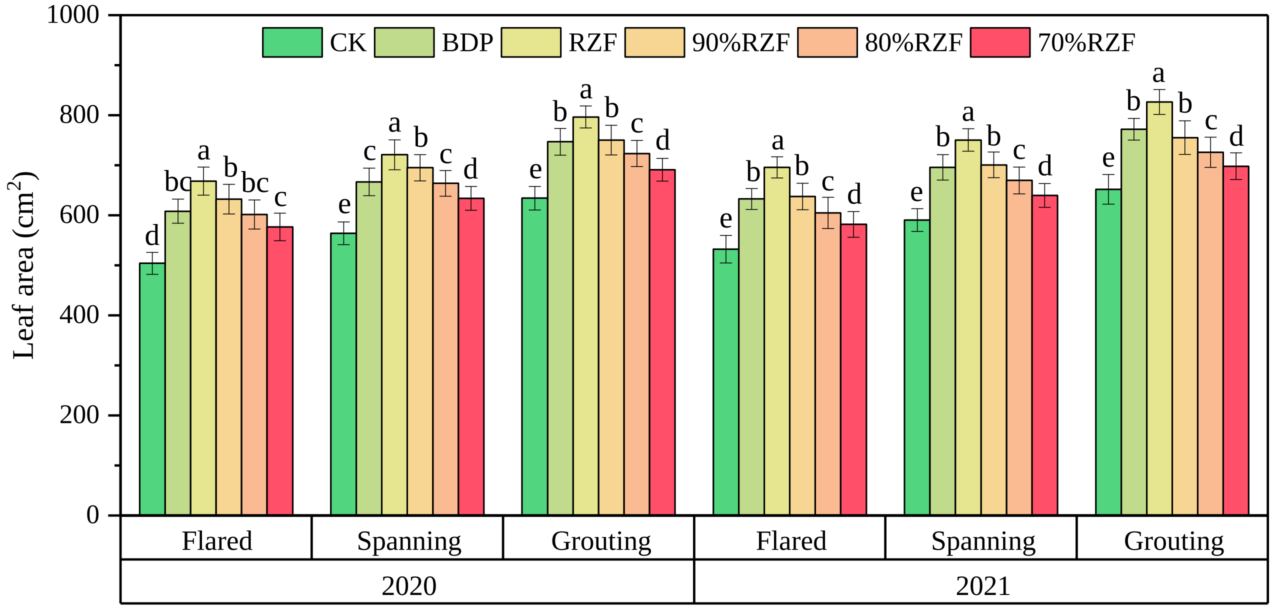

Fig. 3 – Effect of fertilizer application method on maize leaf area

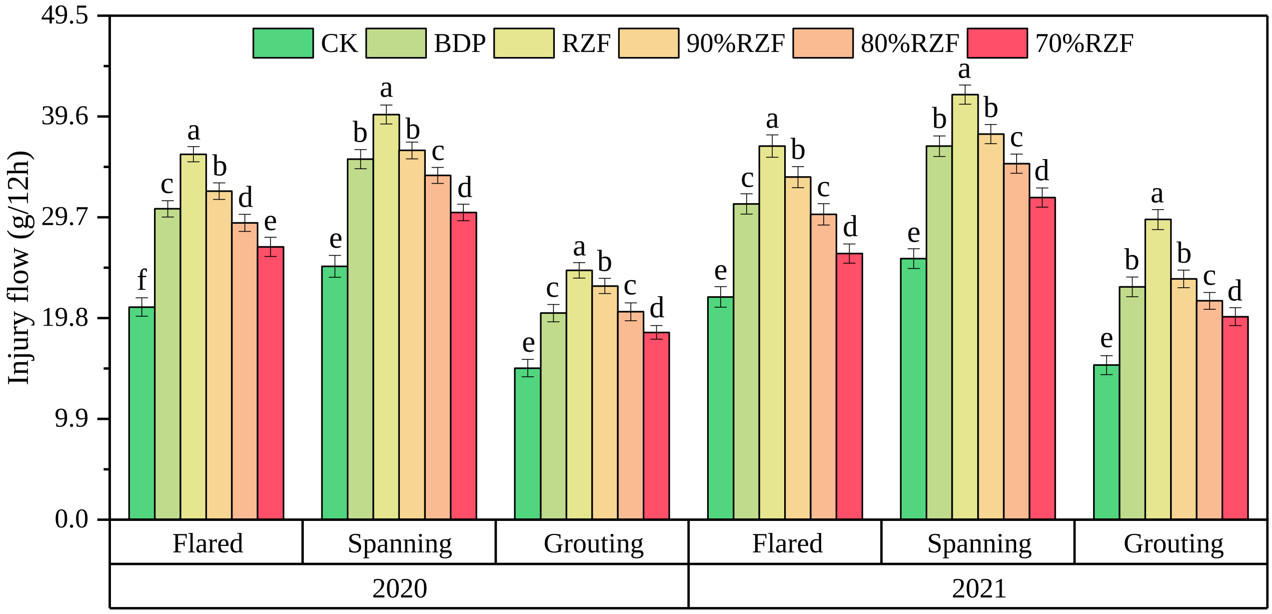

Fig. 4 – Effect of fertilizer application method on maize injury flow

Effect of different fertilizer application methods on maize injury flow

As can be seen from Figure 4, compared with CK, one-time mechanized fertilization in the root zone increased the injury flow by 59.93%-94.21%, and the difference was significant. In the whole growth period, the maize injury flow of RZF was slightly higher than that of BDP by 12.37%-28.92%, and the difference was significant. With the decrease of fertilization rate, the plant injury flow of RZF gradually decreased by 24.18%-32.37%, and the difference was significant. There was no significant difference in maize injury flow between 90% RZF and BDP. RZF had the largest maize injury flow, which indicated that the root system had a stronger ability to absorb water and fertilizer and had a greater potential for increasing yield.

Effect of different fertilizer application methods on maize dry matter mass of root system

As can be seen from Figure 5, compared with CK, one-time mechanized fertilization in the root zone increased root dry matter by 141.94%-144.62%, and the difference was significant. The maize root dry matter of RZF was slightly higher than that of BDP by 10.65%-10.88%, and the difference was significant. The root dry matter of RZF plants decreased gradually by 21.16%-26.73% with the decrease of fertilization amount, and the difference was significant. There was no significant difference in maize root dry matter between 90% RZF and BDP. RZF had the largest root dry matter, indicating that the more developed the root system, the greater the root length and root surface area, the stronger the ability to absorb water and fertilizer, and the greater the potential for increasing yield.

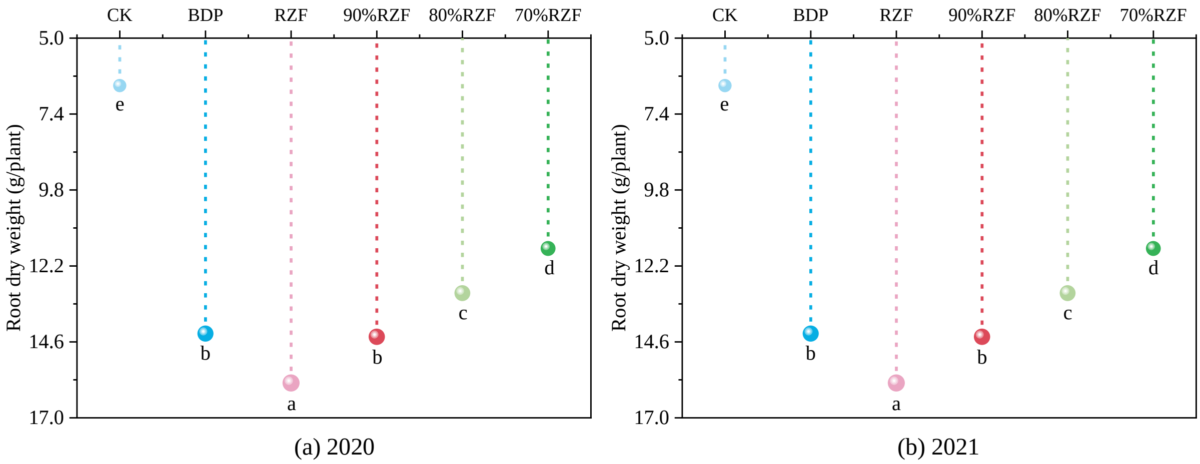

Fig. 5 – Effect of fertilizer application method on maize dry matter mass of root system

Effect of different fertilizer application methods on maize yield and fertilizer utilization

It can be seen from Table 1 that the average 2-year yield of maize under the six treatments was 5700.76 kg/ha~10067.92 kg/ha. The grain yield of BDP and RZF treatments was the highest, and the yield of RZF was 5.83% higher than that of BDP, and the difference was significant. The maize yield of RZF decreased gradually by 15.15% with the decrease of fertilization amount, and the yield difference between treatments was significant when the fertilizer decrease was 10%. The yield difference between BDP and 90% RZF was not significant, indicating that the effect of RZF and BDP on yield was not obvious when losing 10%.

Table 1

Effect of fertilizer application method on maize yield and fertilizer utilization

Treatment	2020			2021		
	Grain yield (kg/ha)	RE (kg/kg)	PFP (kg/kg)	Grain yield (kg/ha)	RE (kg/kg)	PFP (kg/kg)
CK	5424.54 e	-	-	5976.98 e	-	-
BDP	9480.52 b	13.796 b	32.247 e	9545.51 b	14.017 c	32.468 e
RZF	10013.85 a	15.610 a	34.061 d	10121.97 a	15.978 a	34.428 d
90%RZF	9411.58 b	15.068 a	35.569 c	9535.13 b	15.535 ab	36.036 c
80%RZF	8927.27 c	14.893 a	37.956 b	9025.46 c	15.310 ab	38.374 b
70%RZF	8496.95 d	14.929 a	41.287 a	8517.69 d	15.030 b	41.388 a

It can be seen from Table 1 that the 2-year agronomy efficiency of maize under the six treatments was 13.796 kg/kg~15.978 kg/kg. BDP had the lowest agronomy efficiency of 13.796 kg/kg, compared with RZF, 90% RZF, 80% RZF and 70% RZF, the agronomy efficiency increased by 13.57%, 10.33%, 8.59% and 7.72%, respectively, and the differences were significant. There was no significant difference in agronomy efficiency between RZF, 90% RZF, 80% RZF and 70% RZF. Compared with BDP, RZF can effectively improve the agronomy efficiency rate of fertilizers, indicating that root zone fertilization can improve fertilizer efficiency and reduce nutrient loss. It can be seen from Table 1 that the average partial factor productivity of maize in 2 years under the six treatments was 32.357 kg/kg~41.338 kg/kg. The partial factor productivity of BDP was the lowest at 32.357 kg/kg, compared with RZF, 90% RZF, 80% RZF and 70% RZF, the partial factor productivity increased by 5.83%, 10.65%, 17.95% and 27.75%, respectively, and the difference was significant. There were significant differences in partial factor productivity among RZF, 90% RZF, 80% RZF and 70% RZF. Compared with BDP, RZF can effectively improve the partial factor productivity of fertilizer, indicating that root zone fertilization can improve grain yield under the premise of the same fertilization amount.

DISCUSSIONS

Compared with the conventional one-time banding fertilizer application, the one-time mechanized point-applied application of slow-release compound fertilizer in the root zone increased the yield by 5.63% and 6.04% in 2020 and 2021, respectively, indicating that the fertilization method of RZF can increase crop yield. At the same time, there is no significant difference in the yield between 90% RZF and BDP in 2020 and 2021, indicating that RZF cannot reduce the yield compared with BDP when the fertilizer dosage is reduced by 10%, which improves the fertilizer efficiency and utilization rate. Jiang (*Jiang et al.*, 2018) found that RZF increased maize yield by 9.8% compared with BDP, which was higher than the results of this study by 5.63% and 6.04%. Because this paper uses the self-developed maize no-till point-applied fertilization planter, the fertilization position, the spatial distribution of fertilizer particles in the soil, and the accumulation form may change to a certain extent during machine fertilization, resulting in a low degree of yield increase. However, it is also proved from a side view that applying fertilizer to the active growth area of the maize root system and matching the fertilizer nutrients with the nutrient absorption of maize can improve the nutrient utilization rate, increase and stabilize the yield.

Compared with BDP, RZF can increase fertilizer agronomic utilization rate by 12.35% and partial factor productivity by 5.31% while increasing yield. Other scholars also have similar research results. Jiang (*Jiang et al.*, 2018) found that RZF can improve fertilizer agronomic efficiency by 20.96-35.86% and partial factor productivity by 6.44%-8.39% compared with BDP. Zhang (*Zhang et al.*, 2020b) believed that the nitrification of ammonium nitrogen under the condition of point-applied fertilization in the root zone was inhibited by the high concentration of nutrients in the fertilizer field, which delayed the conversion of ammonium nitrogen to nitrate nitrogen and ensured the continuous and efficient supply of nitrogen fertilizer. Zhou (*Zhou et al.*, 2020b) believed that fertilizer point-applied can effectively reduce the contact area between fertilizer particles and soil, resulting in low nutrient release efficiency, prolonging nutrient supply time, and improving nutrient absorption efficiency.

CONCLUSIONS

The one-time mechanized RZF of slow-release compound fertilizer in the root zone increased the yield by 5.84% compared with the one-time BDP, and the difference was significant. The fertilizer agronomic efficiency of RZF was 12.35% and the partial productivity of 5.31% was higher than that of BDP, and the difference was significant. Compared with BDP, RZF has no significant difference in plant height, but there are significant differences in plant stem diameter, leaf area, wound flow and root dry matter mass, indicating that root zone fertilization can promote root growth. It shows that fertilization in the root zone can promote root growth, increase root length and root surface area, resulting in a stronger ability to absorb water and fertilizer, which is further manifested as a significant increase in injury flow, thereby improving the growth and development of shoots, increasing leaf area, and improving photosynthesis intensity, and ultimately achieve fertilizer decrease and increase production.

ACKNOWLEDGEMENT

This work was financially supported by National Key Research and Development Plan of China (2017YFD0700703).

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