EFFECT OF CONTROLLED-RELEASE FERTILIZER ON MAIZE YIELD AND NUTRIENT UPTAKE UNDER A ONE-TIME FERTILIZER LAYERED SYSTEM
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根区一次性分层施肥对夏玉米产量和养分吸收的影响

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ABSTRACT
Currently, maize production in China suffers from many problems such as excessive fertilizer application, inefficient fertilizer use and insufficient agricultural labour. This research explores the efficient fertilization pattern of maize for fertilizer decrease and yield increase by studying the effect of one-time mechanical point-applied fertilization of controlled-release compound fertilizer in the root-zone, on yield and nutrient uptake. There were 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; 3) one-time point-applied fertilization (RZF) 5 cm off seed in the row and 10 cm deep; 4) a layered banding application 5 cm off seed, 10 cm and 20 cm deep between rows at a rate of 3:7 (LBD); 5) a 5 cm off seed, 10 cm deep point-applied fertilization, and 20 cm banding application between rows at a rate of 3:7 (LRZ); 6) a fertilizer reduction of 10% between rows at a rate of LRZ (90% LRZ). The results showed that the one-time mechanical layered application of slow-release compound fertilizer (LRZ and LBD) in the root zone increased yields by 11.97% and 11.15%, respectively, compared to the non-layered application of slow-release compound fertilizer (BDP and RZF), and the differences were significant, indicating that mechanical layered application can replace the BDP mode and achieve increased crop yield. The average increase in agronomic efficiency and partial factor productivity of 25.95% and 11.15% for LBD over BDP and 26.10% and 11.97% for LRZ over RZF were significant, indicating that mechanized stratified fertilizer application can significantly improve fertilizer utilization and reduce fertilizer losses and surface source pollution.

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，通过研究分层施肥（上层穴施下层条施）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），共设 6 个施肥方案，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) 行间偏离种子 5 cm、深 10 cm 和 20 cm 分层条施，且施肥比例为 3：7 (LBD)；5) 行间偏离种子 5 cm、深 10 cm 穴施、20 cm 条施，且施肥比例为 3：7 (LRZ)；6) 减肥 10%行间偏离种子 5 cm、深 10 cm 穴施、20 cm 条施，且施肥比例为 3：7 (90%LRZ)。结果表明，根区一次性机械化分层施用缓释复合肥（LRZ 和 LBD）比不分层施用缓释复合肥（BDP 和 RZF）分别增产 11.97%和 11.15%，且差异显著，说明机械化分层施肥可以代替传统"一炮轰"施肥模式，实现作物增产。LBD 比 BDP 的农学利用率和偏生产力平均增大了 25.95%和 11.15%，LRZ 比 RZF 的农学利用率和偏生产力平均增大了 26.10%和 11.97%，且差异显著，说明机械化分层施肥可以显著提高肥料利用率，减少肥效损失和面源污染。90%LRZ 与 LBD 相比植株高度、茎粗、叶面积、伤流量、根系干物质量和籽粒产量差异均不显著，说明分层穴施肥料是减肥 10%可以实现减肥不减产，节本增效的效果，可为提高作物单产、减少面源污染提高新的研究思路。

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INTRODUCTION

Maize *(Zea mays L.)* is one of the most widely grown cereal crops globally and the consumption and demand is increasing worldwide as the major source of food, feed, and bio-fuel (*Cassman et al.*, 2003). The cultivated area for maize in China is estimated at 42.42 million ha with yield of about 259.23 million tones' year (*Shemi et al.*, 2021). Therefore, increasing maize productivity has become an important aspect to ensure food security (*Usman et al.*, 2021). However, in order to obtain high yields within short periods, growers often use large amounts of fertilizers, which cause fertilizer losses, wasted resources and challenges to sustainable development of agricultural production (*Luan et al.*, 2020; *Ren et al.*, 2020; *Xu et al.*, 2019). The main reason is that fertilizer application technologies and fertilizer application machinery at national level have lower levels than the level of developed countries in the world (*Shi et al.*, 2020; *Wei et al.*, 2019; *Anstoetz et al.*, 2015).

The conventional fertilizer application mode applies fertilizer in a one-time banding fertilizer at a distance of 5~10cm from the seed row and 10 cm deep at the time of corn 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). Recent studies have found that ammonia volatilization and runoff losses are significantly reduced when urea is point-applied to the root zone, greatly improving the utilization of nitrogen fertilizer (*Cao et al.*, 1984; *SavantDe et al.*, 1980). Zhou (*Zhou et al.*, 2020) found that a one-time root zone point-applied application under the furrow full film cover planting method was beneficial to the concentration of nitrogen in the soil tillage layer. Liu (*Liu et al.*, 2017) found that by a single point-applied application of N fertilizer in the root zone of rice, the apparent utilization rate of N fertilizer increased by 22.6%-30.6% and the N loss decreased from 73.0% to 29.7% compared with the previous application. Chen (*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.

Split fertilization generally uses a combination of base and follow-up fertilizers, which increases the number of fertilization operations, reduces agricultural production efficiency, accelerates soil slumping in the cultivated layer, and is prone to crop damage. The one-time layered fertilizer application technology applies the fertilizer required for the crop growth cycle into the soil in layers at one time with the slow-release fertilizer, which can improve the fertilizer efficiency, completely replace the phased fertilizer application. Wang (*Wang et al.*, 1993) found significant yield increases in maize using stratified ratio fertilization, in addition to improving the efficiency of fertilizer application operations and fertilizer utilization. Wang (*Wang et al.*, 2008) found that wheat yield increased by 27% to 46% using stratified fertilization. Wen (*Wen et al.*, 2017) found that stratified strip application of winter wheat substrate could improve dry matter accumulation and yield. Ma (*Ma et al.*, 2019) found that deep fertilization of summer maize with layered fertilization could effectively improve the water retention performance of deep soil, increase the effective phosphorus content in the lower soil layer, improve maize yield and effectively reduce soil water and phosphorus nutrient losses. Zhang (*Zhang et al.*, 2018) found that deep pine layered fertilization of summer maize significantly increased yield by 7.4% to 13.9%, and observation of root microstructure revealed a significant decrease in the proportion of pith cavity to mid-column area and an increase in the number of root ducts.

Based on the above studies, few studies have been reported on the effects of one-time layered point-applied fertilizer application on maize yield. In this paper, the effects of one-time layered point-applied slow-release compound fertilizer application on yield and nutrient use efficiency of maize through a two-year field experiment were investigated, aiming to provide technical support and theoretical support for weight and yield loss and efficiency of maize production.

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 an average annual temperature of 12.4 °C, a frost-free period of 188 days, an average annual sunshine duration of 2714.1 h, an average annual rainfall of 489.8 mm, and a temperate continental monsoon climate, with precipitation accounting for 54% of the annual precipitation during the test period (June-September). The precipitations during the test period (June to September) accounted for 54% of the annual precipitations. The previous crop was winter wheat, with a stubble height of 15-20 cm and a straw volume 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

Maize seeds used in the experiment were "Zhengdan 958", 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; 3) one-time point-applied fertilization (RZF) 5 cm off seed in the row and 10 cm deep; 4) a layered banding application 5 cm off seed, 10 cm and 20 cm deep between rows at a rate of 3:7 (LBD); 5) a 5 cm off seed, 10 cm deep point-applied fertilization, and 20 cm banding application between rows at a rate of 3:7 (LRZ); 6) a fertilizer reduction of 10% between rows at a rate of LRZ (90% LRZ).

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.

Measurement items and methods

Collection and determination of plant samples

Five plants were randomly selected to measure plant height and stalk diameter (diameter of maize stalk base) at the V5 (fifth leaf collars are visible), V10 (tenth leaf collars are visible), R1 (silks emerge from husks) and R5 (more than 50% of kernels are dented) 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 V10, R1 and R5 stages, respectively.

Collection and determination of soil samples

Root system determination: Five plants were randomly selected at the R1 stage of maize, and the soil was dug out with a 30 cm radius and 30 cm depth, rinsed off the soil 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 were randomly selected at the V10, R1 and R5 stage, respectively. At 18:00, the stalk was cut horizontally with a sharp blade from a height of 10 cm above the ground and keep the incision flat, was quickly put on the pre-prepared wound fluid collection bag and fastened with a cable tie. The collection belt is an intact transparent sealed bag with dry absorbent cotton inside. It was weighed before use (W_1) and labelled, collected for 12 hours (the wound fluid should not exceed the saturated absorption capacity of absorbent cotton), the collection bag was removed, and weighed 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 first 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/hm^2) - yield in the control area (kg/hm^2)]/ nutrient application (kg/hm^2)]

Partial factor productivity (PFP, kg/kg) = yield (kg/hm^2) / nutrient application (kg/hm^2)

SPSS 19.0 software was used for variance analysis, and Duncan's new multiple range method was used to analyse 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

As seen in Figure 1, the one-time mechanical fertilizer application in the root zone increased plant height by 22.09% to 39.73% compared to CK, and the difference was significant. Maize plant height was slightly higher in BDP than in LBD at the V5 stage, but it was basically the same in RZF and LRZ. The plant height of maize in LBD increased from 1.19% to 6.04% compared with BDP at the V10, R1 and R5 stages, and the plant height of LRZ increased from 0.87% to 6.60% compared with RZF, and the difference in plant height between fertilizer treatments increased gradually with time. There was no significant difference in plant height between BDP and LBD, RZF and LRZ at the V5 and V10 stages, and the difference in plant height between maize at the R1 stage gradually appeared, and the plant height at the R5 stage with layered fertilization was significantly greater than that without layered fertilization.

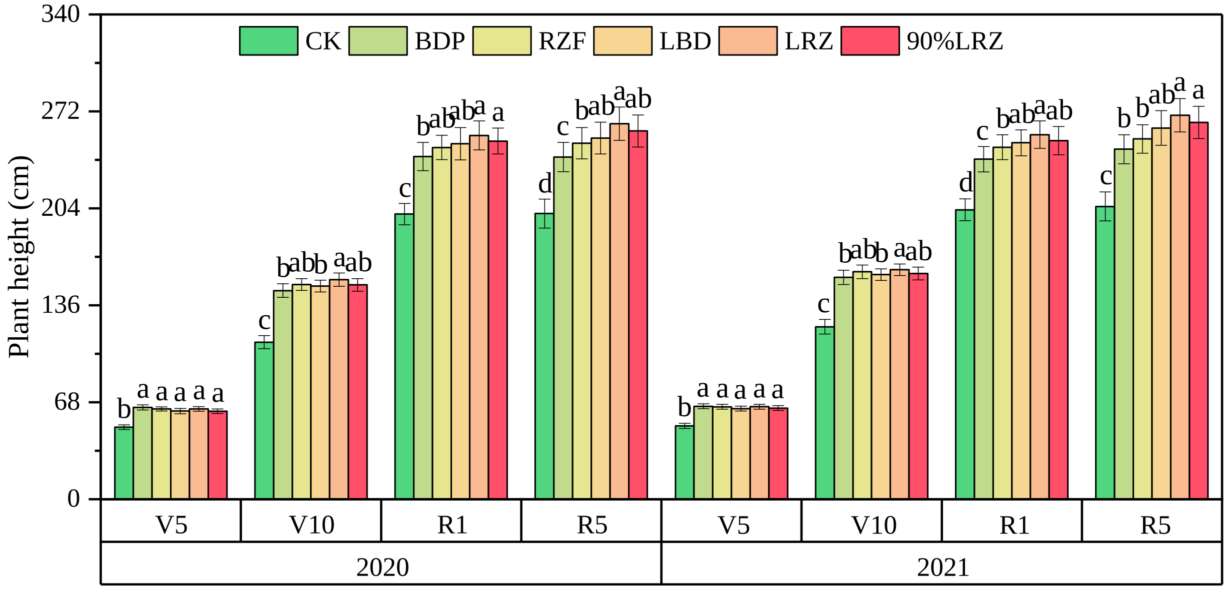

Fig. 1 – Effect of fertilizer application method on maize plant height

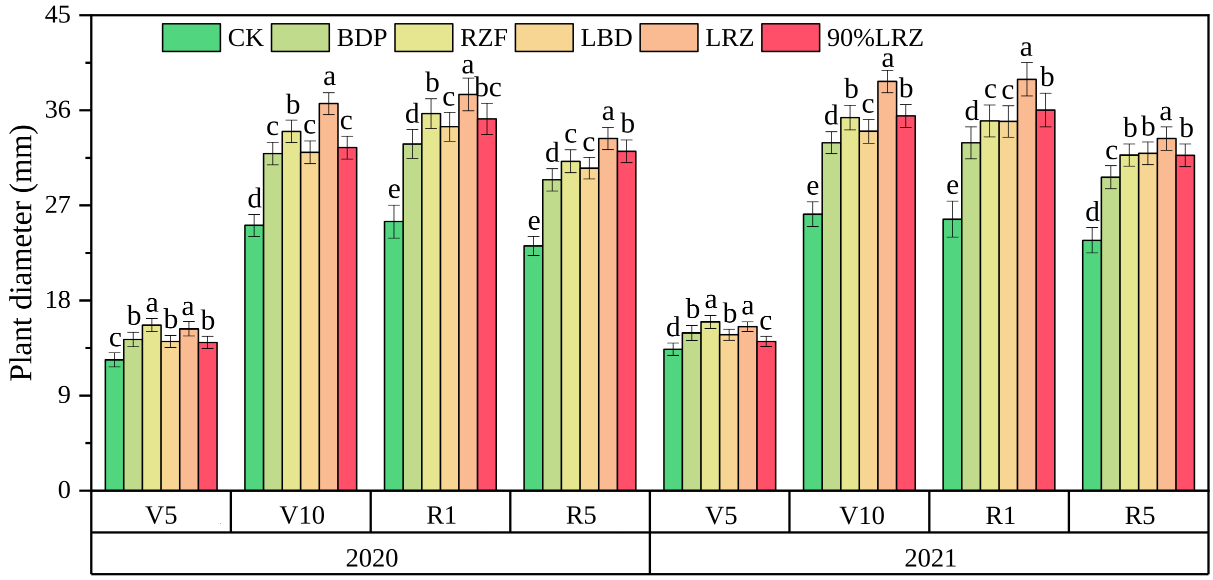

Fig. 2 – Effect of fertilizer application method on maize stalk diameter

As shown in Figure 2, the one-time mechanical fertilization in the root zone increased stalk diameter by 5.46% to 51.53% compared to CK, and the difference was significant. Maize stalk diameter was slightly greater in BDP than in LBD at the V5 stage, but was essentially the same in RZF and LRZ. The stalk diameter of maize in LBD increased from 0.39% to 7.63% compared with BDP at the V10, R1 and R5 stages, and the stalk diameter of plants in LRZ increased from 4.90% to 11.29% compared with RZF. The difference in stalk diameter between different fertilizer treatments increased gradually with time. There was no significant difference in maize stalk diameter between BDP and LBD, RZF and LRZ during the V5 and V10 periods, and the difference in maize stalk diameter gradually appeared during the R1 period, and the stalk diameter of layered fertilizer application during the R5 period was significantly greater than that of non- layered.

Effect of different fertilizer application methods on maize leaf area

As seen in Figure 3, the one-time mechanical fertilizer application in the root zone increased leaf area by 25.78% to 38.79% compared to CK, and the difference was significant. The leaf area of LBD increased by 4.79%~5.09%, 4.40%~4.84% and 3.76%~3.88%, respectively, compared with BDP, and the leaf area of LRZ increased by 4.17%~4.70%, 3.18%~4.96% and 3.76%~3.77%, respectively, compared with RZF at the V10, R1 and R5 stages. The difference in leaf area between different fertilization treatments gradually decreased with time. The leaf area of maize showed significant differences between BDP and LBD, RZF and LRZ during the whole fertility period, and 90% LRZ showed no significant difference in leaf area of maize compared with BDP, indicating that layered fertilization can effectively increase leaf area.

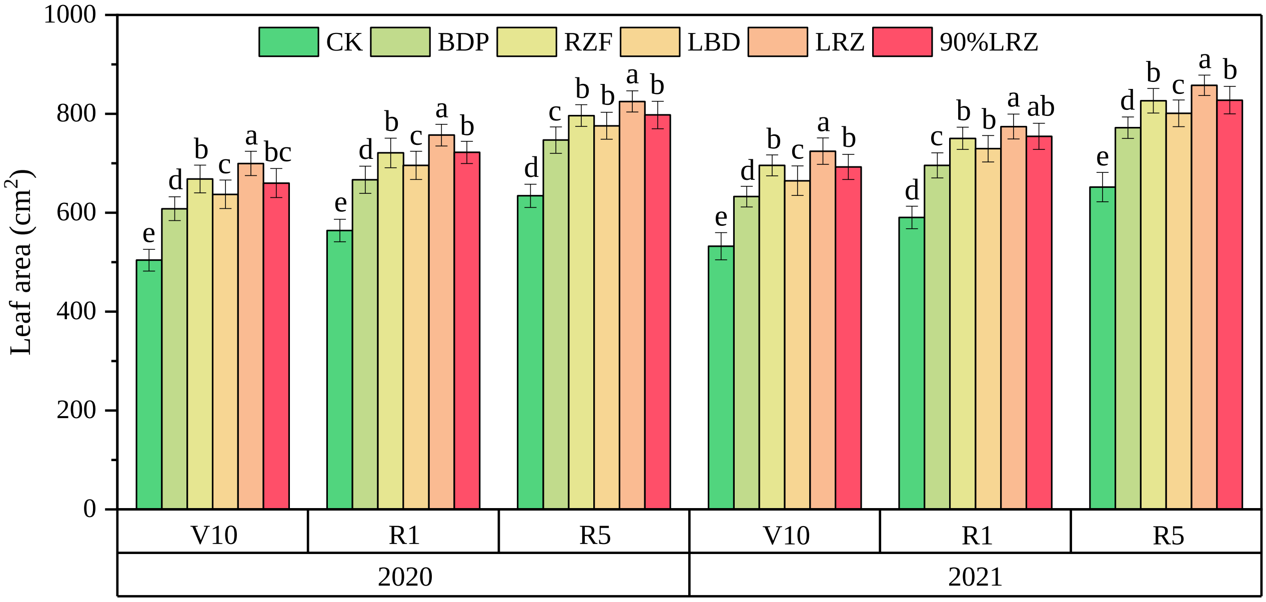

Fig. 3 – Effect of fertilizer application method on maize leaf area

Effect of different fertilizer application methods on maize injury flow

As seen in Figure 4, the one-time mechanical fertilizer application in the root zone increased the injury flow rate by 57.71%~117.17% compared to CK and the difference was significant. Injury flow rate increased by 8.71%~9.29%, 2.20%~7.55% and 12.22%~20.57% in LBD compared with BDP at the V10, R1 and R5 stages, respectively, and increased by 7.12%~7.51%, 7.64%~9.19% and 26.50%~29.38% in LRZ compared with RZF, respectively, and the difference in injury flow rate between different fertilizer treatments gradually increased over time.

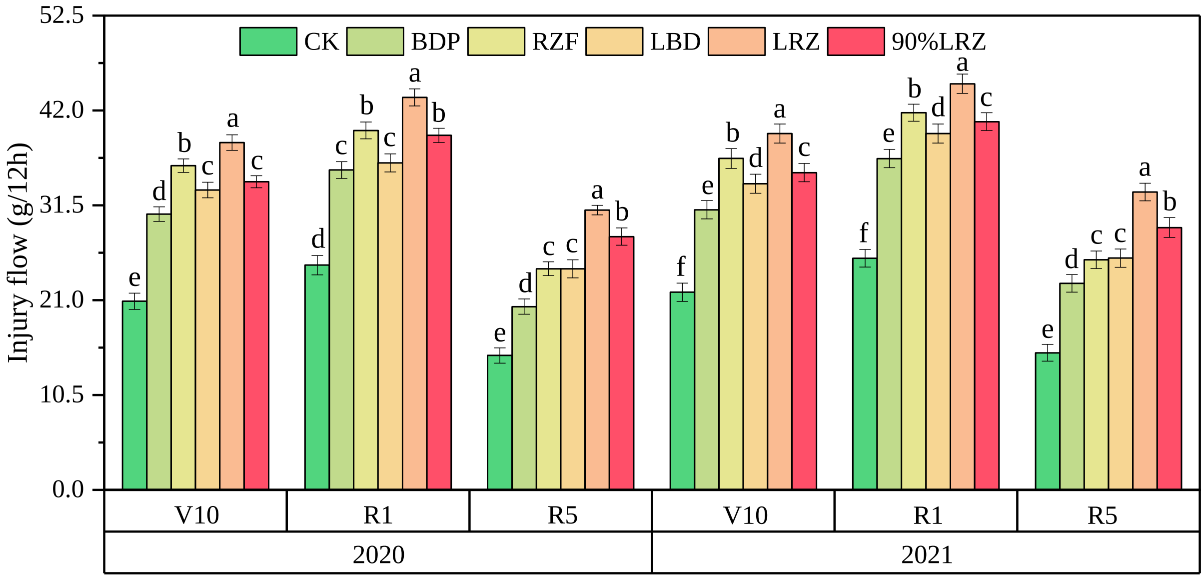

Fig. 4 – Effect of fertilizer application method on maize injury flow

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

As seen in Figure 5, the one-time mechanical fertilization of the root zone increased root dry matter by 161.23% to 189.10% compared to CK, and the differences were significant. The root dry matter increased by 16.18% to 20.41% in LBD compared to BDP and 14.53% to 19.49% in LRZ compared to RZF, and both showed significant differences, indicating that stratified fertilization can effectively increase root dry matter. 90% LRZ showed no significant difference in maize root dry matter compared with LBD and showed significant difference with RZF, indicating that stratified fertilization with upper holes and lower strips could increase root dry matter with reduced fertilizer application.

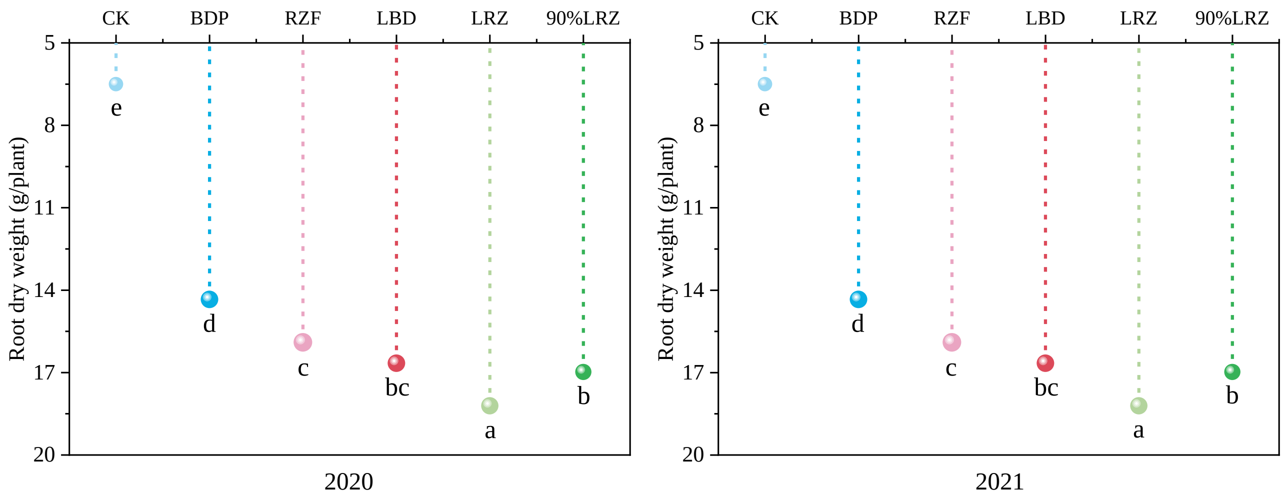

Fig. 5 – Effect of fertilizer application method on maize dry matter mass of root system

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

As it can be seen from Table 1, the average 2-year yield of maize under the six treatments ranged from 5700.76 kg/hm² to 11216.63 kg/hm², and compared with CK, one-time mechanical fertilization in the root zone increased maize yield by 66.87% to 96.76%. LRZ treatment had the highest seed yield and was 11.97% higher than RZF, and LBD was 11.15% higher than BDP seed yield, and all differences were significant, indicating that layered fertilizer application could effectively improve seed yield. Yield in LRZ was reduced by 5.71% when fertilizer application was reduced by 10%. The yield difference between LBD and 90% LRZ was not significant, indicating that the effect of RZF and LBD on yield was not significant when weight loss was 10%, and it can be concluded that fertilizer layered application can reduce fertilizer application but not affect yield.

Table 1

Effect of fertilizer application method on maize yield and fertilizer utilization

Treatment	2020			2021		
	Grain yield (kg/hm²)	RE (kg/kg)	PFP (kg/kg)	Grain yield (kg/hm²)	RE (kg/kg)	PFP (kg/kg)
CK	5424.54 e	-	-	5976.98 d	-	-
BDP	9480.52 d	13.796 d	32.247 c	9545.51 c	14.017 d	32.468 c
RZF	9913.85 c	15.270 c	33.721 c	10121.97 b	15.978 c	34.428 b
LBD	10568.02 b	17.495 b	35.946 b	10580.30 b	17.537 b	35.987 b
LRZ	11198.70 a	19.640 a	38.091 a	11234.56 a	19.762 a	38.213 a
90% LRZ	10574.95 b	19.465 a	39.966 a	10576.98 b	19.473 a	39.973 a

As shown in Table 1, the average 2-year agronomy efficiency of maize under the six treatments ranged from 13.906 kg/kg to 19.701 kg/kg, with BDP having the lowest agronomy efficiency of 13.906 kg/kg. RZF, LBD, LRZ and 90% LRZ showed 12.35%, 25.95%, 41.67% and 40.00% increase in agronomy efficiency compared to them, respectively, and all were significantly different. There was no significant difference in agronomy efficiency between LRZ and 90% LRZ compared to each other. LBD could effectively improve the agronomy efficiency of fertilizer by 25.95% compared to BDP, and LRZ improved the agronomy efficiency by 26.10% compared to RZF, indicating that layered fertilizer application could improve fertilizer efficiency and reduce nutrient loss.

As can be seen from Table 1, the average 2-year partial factor productivity of maize under the six treatments ranged from 32.357 kg/kg to 39.970 kg/kg. BDP had the lowest partial factor productivity of 32.357 kg/kg, while RZF, LBD, LRZ and 90% LRZ had 5.31%, 11.15%, 17.91% and 23.53% increase in partial factor productivity compared to them, respectively, and all were significantly different. The partial factor productivity was significantly different between LRZ and 90% LRZ compared to each other. LBD was effective in increasing fertilizer partial factor productivity by 11.15% compared to BDP, and LRZ increased fertilizer partial factor productivity by 11.97% compared to RZF, indicating that layered fertilizer application can increase seed yield with the same amount of fertilizer application.

DISCUSSIONS

The one-time layered application of fertilizer in the root zone compared with conventional unlayered application increased yields by 11.15% to 11.97% on average in 2020 and 2021. This indicates that the layered fertilizer application method can achieve crop yield increase, while there is no significant difference in yield between 90% LRZF and BDP compared to both in 2020 and 2021, indicating that RZF can be used at 10% fertilizer reduction without yield reduction compared to LBD, which improves the fertilizer efficiency utilization. Other scholars have similar findings, such as Gong (*Gong et al.*, 2019) who found that layered bottom application of slow-release fertilizer promoted the growth and development of late summer maize, increased dry matter accumulation in late summer maize. Zhang (*Zhang et al.*, 2017) found that maize leaf area index, dry matter accumulation, yield and N fertilizer utilization efficiency were significantly higher with layered fertilization technology than BDP under the same N application, and yield and N fertilizer partial factor productivity were increased by 5.5% and 7.9%.

The data showed that in 2020 and 2021 LBD had an average increase in agronomy efficiency and partial factor productivity of 25.95% and 11.15% over BDP, and LRZ had an average increase in agronomy efficiency and partial factor productivity of 26.10% and 11.97% over RZF. LRZ had the highest seed yield of 11216.62 kg/hm^2 and the highest agronomy efficiency of 19.701 kg/kg, and the partial factor productivity was second only to 90% LRZ with 38.152 kg/kg. The combined effect of layered fertilizer application and point-applied application, the upper point-applied application of fertilizer allowed the plants to be thick and strong at the seedling stage because fertilizer point-applied application increased the local nutrient supply concentration in the root zone and fertilizer nutrient uptake rate became greater, promoting plant growth and development. The plant height, stalk diameter, leaf area and injury flow rate were the highest in LRZ at the V5, V10, R1 and R5 stages.

The fertilizer application method of upper layer fertilizer point-applied application and lower layer fertilizer banding application makes the spatial distribution pattern of fertilizer particles in the tillage layer soil approximate to a cone platform with small top and large bottom, while the root system of maize plant in the spatial distribution approximate to a cone, so the fertilizer supply is completely concentrated in the coverage of maize plant root system, which avoids nutrient wastage in space, and at the same time promotes deep rooting to avoid plant collapse. Therefore, layered root zone fertilization is currently one of the best fertilizer application methods to improve fertilizer utilization efficiency, as well as a new research idea for improving crop yields.

CONCLUSIONS

The one-time mechanical LRZ and LBD fertilizer application in the root zone increased yields by 11.97% and 11.15%, respectively, compared with BDP and RZF, and the differences were significant, indicating that mechanical layered application can replace the BDP and phased application patterns to achieve increased crop yields. The average increase in agronomy efficiency and partial factor productivity was 25.95% and 11.15% for LBD over BDP and 26.10% and 11.97% for LRZ over RZF, and the differences were significant, indicating that mechanized layered fertilizer application can significantly improve fertilizer utilization and reduce fertilizer losses and surface source pollution.

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