Renewable Agriculture and Food Systems

cambridge.org/raf

Development status and trends in side-deep fertilization of rice

Jinfeng Wang, Zhentao Wang, Wuxiong Weng, Yuanfeng Liu, Zuodong Fu and Jinwu Wang

College of Engineering, Northeast Agricultural University, Harbin 150000, China

Review Article

Cite this article: Wang J, Wang Z, Weng W, Liu Y, Fu Z, Wang J (2022). Development status and trends in side-deep fertilization of rice. *Renewable Agriculture and Food Systems* **37**, 550–575. https://doi.org/10.1017/S1742170522000151

Received: 29 November 2021
Revised: 24 March 2022
Accepted: 5 April 2022
First published online: 27 June 2022

Key words:
Fertilizer; machine; rice; side-deep fertilization

Author for correspondence:
Jinwu Wang,
E-mail: jinwu_329@163.com

Abstract

Overuse of fertilizer is detrimental to the sustainability of crop production from an economic and environmental perspective. While rice side-deep fertilization technology can significantly improve fertilizer utilization efficiency, improve crop yield and reduce environmental pollution caused by improper use of fertilizer compared with conventional fertilization methods. Therefore, side-deep fertilization technology has an important role in the sustainable development of agriculture. This article describes fertilizer selection, side-deep fertilization devices and the effects of side-deep fertilization technology on rice plants and soil. We summarize the types and characteristics of side-deep fertilizers and their ratios and modes. The basic principles and characteristics of the key components of mechanical fertilization devices are described in detail, including fertilizer discharging devices (rotating disc type, outer groove wheel type, screw type), fertilizer conveying devices (pneumatic, mechanical forced type) and sensors. The effects and mechanisms of side-deep fertilization on rice growth, yield, quality, fertilizer utilization efficiency and soil microorganisms are summarized. Finally, based on current research on side-deep fertilization, future directions are identified to aid the development of this promising technology.

Introduction

Rice is one of the most important food crops, with about 60% of the world's population using it as their staple food. As food demand is rapidly increasing with population growth, many agricultural producers are cultivating high-yield food crops that require large amounts of chemical fertilizers. However, the growth rate in food production is not proportional to that of chemical fertilizer use. Excessive chemical fertilizer input is a serious issue, as it not only increases agricultural production costs and wastes resources but also hardens cultivated land and acidifies the soil, reducing the yield potential of arable land. This can form a vicious circle where increasing amounts of chemical fertilizers are required to obtain the same crop yield. On the other hand, groundwater contamination, eutrophication, emission of greenhouse gases and air pollution are negative externalities deriving from the improper use of fertilizers. Therefore, fertilizer management is crucial for the economic and environmental sustainability of cropping systems. Rice side-deep fertilization is a fertilization management and technical system (Fig. 1) that can effectively improve fertilizer utilization efficiency, increase rice farming income and reduce environmental pollution compared with conventional fertilization methods. It is of great significance to the mechanization of rice production and the sustainable development of agriculture.

In conventional fertilization operations, a basal fertilizer is usually applied to the ground surface manually or with a fertilizer spreader when the ground is trimmed. Then, a soil preparation machine is used to mix the fertilizer and soil. After soaking the field and transplanting seedlings, topdressing with tiller fertilizer and panicle fertilizer is carried out. Conventional methods have a high labor intensity and may create an uneven fertilizer distribution that causes inconsistent nutrient absorption by rice seedlings, directly affecting the yield and quality of rice. Side-deep fertilization applies a basal fertilizer, tiller fertilizer and panicle fertilizer once or twice during the rice seedling transplanting stage at a position 3–5 cm away from the root and a depth of 5–8 cm. The number of required operations is reduced and fertilizer is applied at a certain distance from the roots to avoid root damage and burning of the seedlings. In addition, the fertilizer is covered by soil, which reduces losses due to drainage and improves utilization efficiency. The use of slow-release fertilizers can also enhance root vitality, ensuring that the rice will turn green and allow tillering without topdressing. Disease resistance and lodging resistance will also be enhanced.

Rice side-deep fertilization requires the use of a certain device. The operating environment of paddy fields is different from that of dry fields, so the traditional ditch discharging method does not work well in paddy fields. Water and mud will affect the discharge of fertilizer from the bellows of the application device. Therefore, side-deep fertilization devices have unique

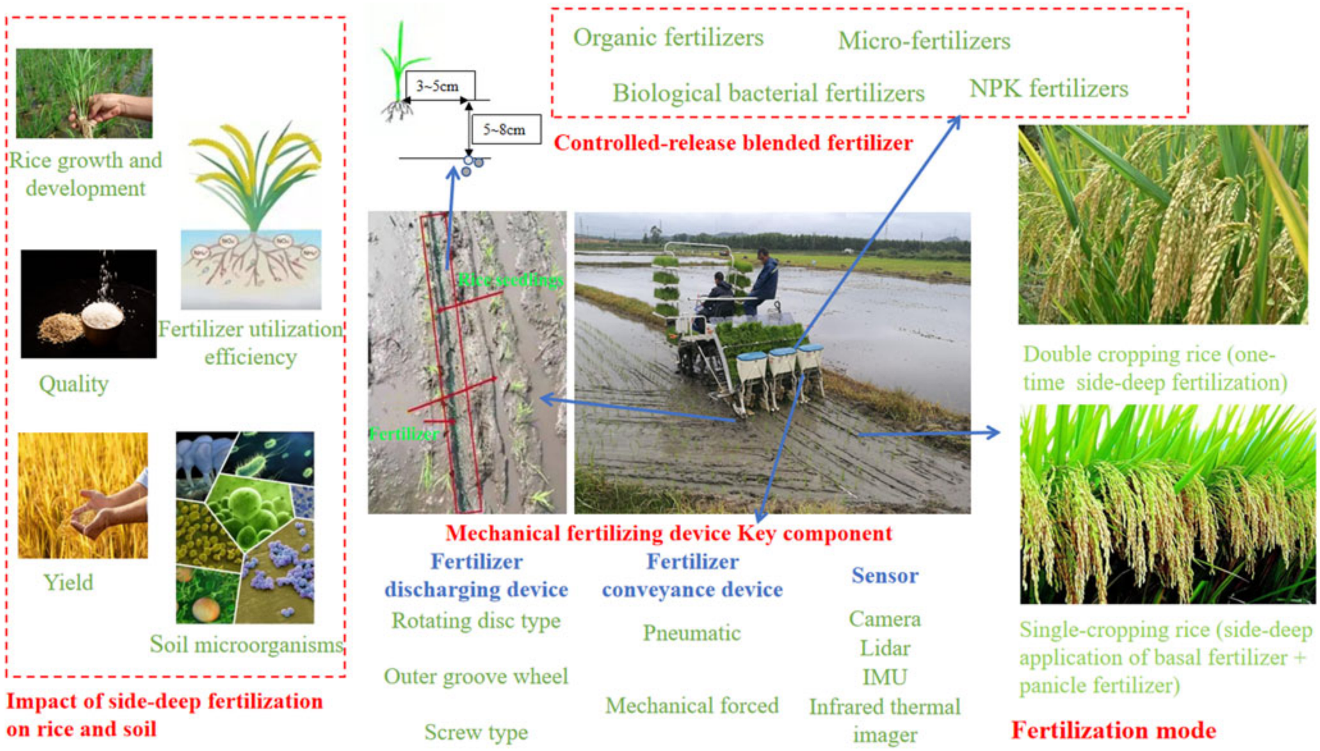

Fig. 1. Side-deep fertilization technology of rice.

characteristics, and rice fertilization machinery is closely related to rice planting methods. One is the direct-seeded mechanized rice cultivation system used in Europe and America. A fertilizer machine performs fertilization operations or simultaneous spraying herbicide and fertilization. The second is a rice transplanting mechanized cultivation system used in China, Japan and South Korea. Rice is transplanted mechanically while side-deep fertilization is generally performed simultaneously. However, the degree of mechanization in rice side-deep fertilization techniques remains relatively low. To improve the level of mechanization and fertilizer utilization efficiency, side-deep fertilization equipment has been a focus of much research. Many mechanical devices have been independently designed and applied to rice production. However, many key technologies require further study. Because the efficacy of side-deep fertilization devices is significantly influenced by the fertilizer used, a special fertilizer is also required.

This article describes the fertilizer selection, the side-deep fertilization device and the impact on rice plants and soil in the rice side-deep fertilization technology. On this basis, future directions for the development of side-deep fertilization technology are proposed. It is expected to provide a reference for accelerating the promotion of side-deep fertilization technology and the optimization of key technologies.

Fertilizer types and modes for side-deep fertilization

Fertilizer types and characteristics

An appropriate fertilizer is key to the success of rice side-deep fertilization technology. Common fertilizers on the market mainly include organic fertilizers, micro-fertilizers (i.e., fertilizers containing trace elements), biological bacterial fertilizers and NPK (nitrogen, phosphorus and potassium) fertilizers. To reduce the number of fertilization instances required, slow- and controlled-release fertilizers are widely used in rice side-deep fertilization, which are classified according to various standards (Wu *et al.*, 2021). For example, according to the preparation process, they can be divided into chemical modification, physical coating and biochemical inhibition types (Azeem *et al.*, 2014). Slow- and controlled-release fertilizers can release nutrients at a suitable rate for the rice plant's requirements, which can reduce nutrient losses and improve fertilizer utilization efficiency and rice yield. The combination of controlled-release fertilizer and side-deep fertilization is key to reducing fertilization costs and increasing rice yield and production efficiency (Rahman *et al.*, 2021) (Table 1).

During the side-deep fertilization of rice, the ground is muddy and the working environment is humid. Therefore, the fertilizer requires a stable composition, good surface compression resistance, uniform particle size distribution and stable water absorption characteristics (Massoudi, 2001; Linquist *et al.*, 2012). Wang *et al.* (2020) analyzed more than ten mainstream granular fertilizers, including slow- and controlled-release fertilizers, special rice fertilizers, compound fertilizers, blended fertilizers and controlled-release urea, and finding that their average particle size was 3–4 mm. The fertilizer with the best stability was 'Heart to Heart' controlled-release urea, which basically does not absorb water. The fertilizers 'Yimaishi', 'Maoshi', 'Yara YARA', 'Wanli Shennong', 'Wolft Smart Film Star', 'Sinochem Fuwannong', 'Taiwan Qingshang Yicheng' and 'Liaoning Jinda Shengyuan' all exhibited <8% water absorption over 24 h, which is relatively stable. The study noted that a fertilizer particle size of 2–5 mm is important for accurate fertilization. For blended fertilizers, Cao *et al.* (2019) pointed out that the average dominant

https://doi.org/10.1017/S1742170522000151 Published online by Cambridge University Press

Table 1. Physical and chemical properties of NPK fertilizers

Fertilizer name	Appearance	Place of origin	Nutrient content (%)	Size guide number (SGN)	Uniformity index (UI)	Hardness (N)	Density (g cm^{-3})	Repose angle (°)
Urea	Round	Inner Mongolia	N ≥ 46.4	340	42.98	11.65	0.73	38.46
Sulfur-coated urea	Round	Shanxi	N ≥ 37	342	49.96	2.06	0.73	37.81
Slow-release fertilizer	Round	Shandong	N ≥ 45	305	47.07	13.27	0.75	39.16
NH_4Cl	Irregular	Jiangsu	N ≥ 25	377	49.94	0.20	0.73	39.81
NH_4Cl	Irregular	Liaoning	N ≥ 25.4	365	46.54	12.35	0.77	38.95
NH_4Cl (wet)	Irregular	Jiangsu	N ≥ 24	351	41.68	47.53	0.71	42.27
$(NH_4)_2SO_4$	Irregular	Heilongjiang	N ≥ 20.5	469	0.00	0.20	0.87	40.03
DAP	Round	Guizhou	Total ≥ 55	345	60.80	39.10	0.95	36.41
DAP	Round	Hubei	Total ≥ 60	300	47.16	39.63	0.95	34.90
DAP	Round	Guizhou	Total ≥ 57	326	47.67	41.38	0.95	34.69
DAP	Round	Guizhou	Total ≥ 64	343	60.49	40.21	1.05	34.69
DAP	Round	Beijing	Total ≥ 64	340	46.91	39.54	1.02	37.77
DAP	Round	Hebei	Total ≥ 64	264	47.24	27.47	0.94	36.21
DAP (Zn fulvic acid)	Round	Beijing	Total ≥ 64	298	48.64	40.02	0.96	40.36
MAP	Round	Chongqing	Total ≥ 64	291	46.03	41.13	0.84	39.57
MAP	Round	Yunnan	Total ≥ 64	296	46.21	16.90	1.01	39.90
KCl	Irregular	Canada	K_2O ≥ 60	281	47.27	23.55	1.04	42.58
KCl	Irregular	Germany	K_2O ≥ 60	281	42.47	48.47	1.03	42.27
KCl	Irregular	Qinghai	K_2O ≥ 59	281	43.06	37.65	1.07	42.25
KCl	Irregular	Jilin	K_2O ≥ 60	346	36.65	28.54	1.04	41.19
K_2SO_4	Irregular	Russia	K_2O ≥ 50	348	40.27	27.05	1.19	42.72
K_2SO_4	Round	Jilin	K_2O ≥ 50	348	42.59	38.46	1.13	42.30

particle size and angle of repose of raw material fertilizers are the main factors affecting nutrient separation during the application of blended fertilizers. When the size guide number of the raw material fertilizer is between 340 and 348, it is more suitable for blending, and the smaller the difference between the average dominant particle size, the more uniform the nutrient distribution. Selecting raw material fertilizers with a smaller angle of repose and reducing the difference between the angles of repose can reduce nutrient separation in blended fertilizers.

Fertilizer ratio and fertilization mode

Reasonable nutrient management improves fertilizer utilization efficiency and yield by meeting the nutrient requirements of plants throughout the growth period and ensuring the effectiveness of nutrients. Excessive nutrient supply wastes fertilizer, while insufficient supply decreases yield (Khanal *et al.*, 2014). The combined application of nitrogen and other fertilizers (especially phosphorus and potassium fertilizers) can effectively increase rice yield and nitrogen fertilizer use efficiency (Sun *et al.*, 2013). This requires balancing the plant's nutrient demand and nitrogen supply (especially soil nitrogen nutrition and nitrogen fertilizer application) throughout the growth period (Cui *et al.*, 2008). The absorption ratio of high-yield rice to N, P_2O_5 and K_2O is 2:1:2.3 or 1:0.45:1.2. This is an indicator that reflects the balance between the three nutrients and is used to guide field fertilization (Ling, 2007). However, for the subtropical region, Behera and Panda (2013) pointed out that N:P_2O_5:K_2O as 2:1:1 is the most suitable fertilizer treatment for rice crop among studied treatments. Therefore, field fertilization needs to be done according to local soil characteristics and fertility, which are determined by soil testing and formula fertilization testing (Table 2).

In addition to the combined application of nitrogen, phosphorus and potassium fertilizers, the combined application of organic–inorganic fertilizers, macronutrients and medium and trace elements is also a hotspot of research. The combined application of nitrogen, silicon, zinc and other trace fertilizers can delay leaf senescence, improve leaf photosynthetic characteristics and increase the nitrogen and crude protein contents of rice grains (Yamuangmorn *et al.*, 2020). The combined application of organic fertilizer and inorganic nitrogen fertilizer increases the net photosynthetic rate of rice functional leaves, promotes the absorption and utilization of nitrogen by rice, increases rice yield and improves rice quality and soil physical and chemical

Table 2. Typical fertilization machinery

Machine name	Manufacturer	Image	Performance parameters	Technical features
JD4940 machinery	John Deere Corporation		Four-valve, six-cylinder 'Power Tech™ Plus' diesel engine with a working width of 36 m and a tank capacity of 4542 liters	Good transmission system and reliable structure, which greatly improve productivity
AXIS50.2W fertilizer spreader	French Kuhn Corporation		Maximum working width of 50 m, maximum fertilization efficiency of 500 kg min^{-1} and working speed of 20 km h^{-1}	The driver can control and adjust the drop point of the fertilizer particles on the spreading disc in the cab, so as to easily adjust the working width
2FH type side-deep fertilizer applicator	Yongxiang Agricultural Machinery Equipment Co., Ltd.	 	The volume of the fertilizer box is 75 liters and the working width is 1–6 m. The sowing quantity can be adjusted in a step-less manner with variable speed	A speed sensor provides vehicle speed information to the controller, which automatically adjusts the fertilizer rate. A position sensor provides the controller with information on the lifting mechanism, and the controller automatically starts or stops fertilizing accordingly

(*Continued*)

Table 2. (*Continued.*)

Machine name	Manufacturer	Image	Performance parameters	Technical features
PZ60-ADTLF Type ride-type high-speed Transplanter (2FH-1.8B type side-deep fertilizer applicator)	Iseki Corporation	 	An outer trough wheel discharges fertilizer to an air conveying fertilizer. It can cover 6 rows, the capacity of the fertilizer box is 60 liters. It applies solid spherical granular fertilizer with a diameter of about 2–4 mm. The fertilization rate is 90–750 kg hm^{-2}, the side of the fertilization position is 45 mm and the depth is 50 mm. Supporting operation efficiency is 0–0.53 $hm^2 h^{-1}$	Grooved wheels are arranged in a two-stage staggered arrangement, which reduces the pulsation phenomenon of the outer grooved wheel when discharging fertilizer. The amount of fertilizer is steplessly adjusted by turning a handle
YR60D riding high-speed rice transplanter (2FC-6 side-deep fertilizer applicator)	Yanmar Corporation	 	Uses rotary disc-type fertilizer discharging and air conveying-type fertilizer. Covers 6 rows, fertilizer box capacity is 78 liters, uses solid spherical granular fertilizer with a diameter of 2–5 mm, the fertilization range is 60–915 kg hm^{-2}, the side of the fertilization position is 50 mm, and the depth is 40 mm. Supporting operation efficiency is 0–0.55 $hm^2 h^{-1}$	Stirring and blanking prevent fertilizer sticking. A sprocket divides the material and mixes the fertilizer in a precise amount, combined with a fine-tuning knob to steplessly adjust the amount of fertilizer applied

2ZGQ-8D riding high-speed rice transplanter (2FH-1.8A type side-deep fertilizer applicator)	Kubota Corporation	 	Uses an outer trough wheel to discharge fertilizer and air conveying fertilizer. Covers 8 rows, fertilizer box capacity is 73.5 liters, applies solid spherical granular fertilizer with a diameter of about 2–4 mm, adjustment range is 150–900 kg hm^{-2}, the side of the fertilization position is 45 mm and the depth is 20–50 mm. Operating efficiency is 0–0.42 hm^2 h^{-1}	A pneumatic fertilizer conveying system absorbs hot air around the engine to ensure that the airflow inside the fertilizer pipeline is dry. This reduces clogging caused by deliquescence of fertilizer in the pipeline
HTO-6 side-deep fertilizer applicator	Hosan Corporation		Uses an outer trough wheel to discharge fertilizer and air conveying fertilizer. Covers 6–8 rows, the fertilization rate is 60–960 kg hm^{-2}, and uses solid spherical granular fertilizer with a diameter of about 2–5 mm	The base of the fertilizer applicator can be installed with a variety of different brands and models of rice transplanters, with strong versatility

properties (Pan *et al.*, 2009). Microbial fertilizers can increase the nitrogen utilization rate, thereby increasing yield using less fertilizer. As the amount of nitrogen application decreases, the nitrogen utilization rate increases (Chen *et al.*, 2010).

Conventional rice fertilization is generally based on a basal fertilizer, tillering fertilizer and panicle fertilizer used three to four times. Panicle fertilizers are divided into two types: flower-promoting fertilizer and flower-retaining fertilizer. Rice side-deep fertilization generally uses slow- and controlled-release fertilizer and deep burial strip application, which can reduce the number of fertilization instances required. Current fertilization modes mainly include 'single-dose deep fertilization at transplanting with 100% controlled-release fertilizer' and 'deep fertilization of 70% controlled-release fertilizer and topdressing of 30% quick nitrogen'. In 'single-dose deep fertilization at transplanting with 100% controlled-release fertilizer', nutrients are applied to paddy soil once during machine planting, which saves labor. 'Deep fertilization of 70% controlled-release fertilizer and topdressing of 30% quick nitrogen' applies a conventional basal fertilizer and a tiller fertilizer to the paddy soil during machine transplanting, and artificial application of one topdressing according to the growth of the rice.

According to recent research, the fertilization mode should be determined according to the rice season and variety type (Wang *et al.*, 2020). For double-cropping rice or single-cropping conventional rice with a short growth period, the yield difference between single and multiple fertilization is not obvious, and one-time side-deep fertilization can be used. For single-season rice with a long growth period, such as indica–japonica hybrid rice, the growth period is 140–165 days. The demand for nitrogen, phosphorus and potassium for rice growth is high and one-time fertilization often affects yield. Hence, 'deep fertilization of 70% controlled-release fertilizer and topdressing of 30% quick nitrogen' is recommended, which is consistent with the goals of obtaining large panicle and increasing the seed setting rate in single-cropping indica–japonica hybrid rice (Qin *et al.*, 2017; Huang *et al.*, 2021). In addition, Corbin *et al.* (2016) pointed out that rice has produced optimum grain yields when fertilizer is applied with a split application.

Mechanical fertilizing device

At present, rice planting methods include direct seeding and seedling transplantation. Among them, direct seeding machinery is mainly used in Europe and the Americas, with fertilizer spreaders used for fertilization (Crusciol *et al.*, 2010). Seedling raising and transplanting machinery is mainly used in China, Japan and other Asian countries, and operates at the same time as fertilization. Fertilization machinery in European and American countries mainly includes centrifugal and pneumatic fertilizer applicators (Table 2). Centrifugal fertilizer applicators use a centrifugal discharging device to apply solid fertilizers and have the advantages of simplicity and low cost. Pneumatic fertilizer applicators mainly use liquid fertilizers and a high-speed fan. The airflow provides pressure to nozzles to achieve wide and efficient spreading, which has the advantages of covering a large working area and high efficiency. Representative machinery includes the SPW series fertilizer spreaders produced by Gamberini, Italy, and the Flexi Soil variable fertilizer planter produced by the Case Company. However, none of these fertilizing machines can achieve side-deep fertilization of rice.

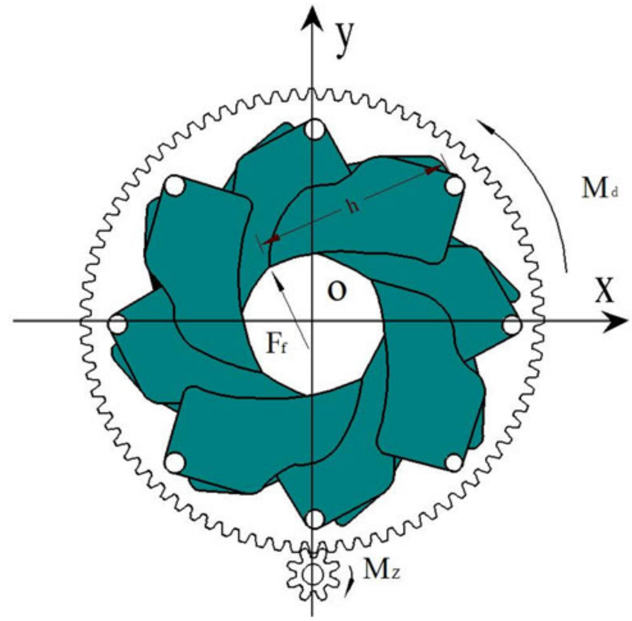

Fig. 2. Force diagram of blades in the XOY plane.

Side-deep fertilization machinery is the basis of the side-deep fertilization of rice (Table 2). Japan has studied side-deep fertilization technology since the 1970s, showing that it saves fertilizer and increases yield. Japan is committed to developing related equipment suitable for the side-deep fertilization of rice. Japanese companies represented by Kubota, Iseki and Yanmar have designed and developed a series of rice side-deep fertilization machines. The supporting equipment for mechanical transplanting and side-deep fertilization has achieved product serialization and standardization (Yao-Ming *et al.*, 2005). Some well-known agricultural machinery companies in China and South Korea have conducted research and development into side-deep fertilization devices for rice. They have developed pneumatic type and screw-push-type side-deep fertilization devices that are matched with rice transplanters. The key components of rice side-deep fertilization machinery are the fertilizer discharging device and fertilizer conveying device. There are many types of fertilizer discharging devices, mainly including rotary disc, outer groove wheel and screw types. They are commonly used to discharge crystalline fertilizers, compound fertilizer granules and dry powdered fertilizers. For fertilizer conveying devices, there are mainly pneumatic and mechanical forced-feeding devices. Among them, pneumatic devices have lower requirements in terms of the surface performance of the fertilizer. Generally, ordinary compound fertilizers can also be used, but they often cause blockages that cause poor fertilizer discharge. Mechanical forced fertilizer conveying devices have a strong ability to actively discharge fertilizer but have high requirements for the physical properties of the fertilizer surface, especially the resistance to compression and fragmentation (Yang *et al.*, 2003).

These types of equipment are mainly composed of a fertilizer box installed at the rear of the rice transplanter, a mechanically driven fertilizer discharge device and a conveying device near the transplanting mechanism. During normal operation, fertilizer from the fertilizer tank is uniformly and quantitatively discharged into the conveying device. An opener divides the mud to form grooves. The fertilizer is affected by wind (or mechanical thrust)

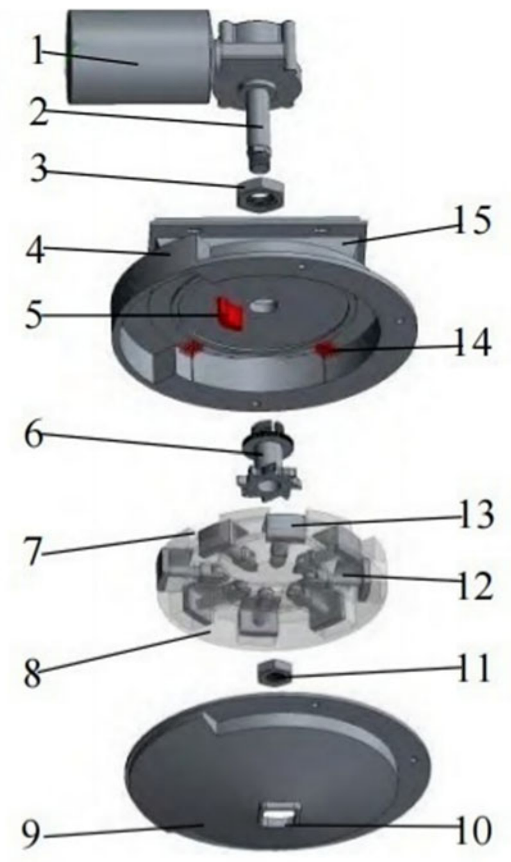

Fig. 3. Disc ejection type fertilizer discharging device: (1) drive motor, (2) fertilizer shaft, (3) fertilizer fastening nut, (4) upper shell body, (5) curved convex, (6) fertilizer adjustment device, (7) fertilizer trough, (8) fertilizer disc, (9) lower shell body, (10) fertilizer outlet, (11) fastening nut, (12) pressure spring, (13) fertilizer ejector pin, (14) fertilizer scraping brush, (15) fertilizer inlet.

and gravity. As the transplanter advances, the fertilizer will be evenly delivered to a designated position to the side of the seedlings, thereby completing side-deep fertilization. At present, such equipment can only achieve continuous and uniform fertilization in strips, which uses 20–30% less fertilizer than traditional manual fertilization methods. However, there are still some problems, such as the transplanter continuing to discharge fertilizer when it slips or turns around.

Key component-fertilizer discharging device

Rotating disc type

A rotating disc type fertilizer discharging device can discharge crystalline fertilizers, compound granular fertilizers and powdered dry fertilizers with good fluidity. This type includes centrifugal disc, scraper disc, impeller disc, etc. The disc and fertilizer guide cone are driven by a ground wheel through a chain and bevel gear and make circular motions relative to the fertilizer tank. When working, the fertilizer falls from the bottom of the fertilizer box into the fertilizer discharging disc. As the disc rotates to reach the scraper, fertilizer then rises along the rising angle of the scraper and, finally, falls into the soil through pipe. Patterson and Reece (1962) first studied the movement of granular fertilizer on the disc, which laid the foundation for the construction of a mathematical model of the disc fertilizer applicator. Villette *et al.* (2005) studied the motion of fertilizer particles on a rotating disc and analyzed the ratio of the horizontal radial component to the horizontal tangential component of the velocity when the fertilizer particles leave the rotating disc. This provided a theoretical basis for the design of later disc fertilizer applicators. Cool *et al.* (2014) constructed a trajectory model of fertilizer particles after they leave the disc and studied the influence of their rotation on their trajectory in the air and the position of the landing point. The results show that the rotation of fertilizer particles after leaving the horizontal disc has an important influence on the position of the drop point. Jin-Feng *et al.* (2018) and others designed a blade-type fertilizer regulation mechanism. The friction between the fertilizer particles and leaves was analyzed. Each blade is only subject to the pressure F_N of the fertilizer particles and the frictional force F_f between the blades during operation (Fig. 2). Further, when the equipment is properly calibrated, external factors play a far more important role (Simon *et al.*, 2016). Hofstee and Huisman (1990) pointed out that the coefficient of friction, the aerodynamic resistance, the particle size and particle size distribution are most important, because they affect the diffusion mode to a great extent. Marcello *et al.* (2013) found that the terminal velocity of fertilizer particles is related to measurable physical properties (mass, shape, size) of the product, and physical features of the individual particles determine the distribution pattern.

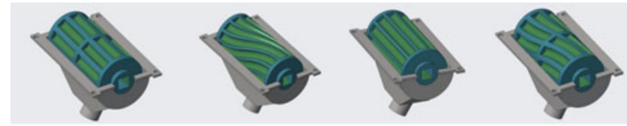

Fig. 4. Four different types of outer groove wheel fertilizer discharging devices.

Most of the side-deep fertilizer applicators produced by Yanmar and other companies adopt a horizontal disc structure. By changing gear wheels with different apertures, the gear speed is adjusted to adjust the fertilizer rate. The fertilizer stability and uniformity of application are better, but the structure is more complex. They have high installation accuracy, difficult maintenance and relatively high fertilizer requirements, so need to be used in conjunction with a specific fertilizer type. In order to improve the versatility of the device, Jin-Feng *et al.* (2021) designed a disc ejection-type side-deep fertilization device that can adjust the fertilization rate by changing the effective working length of the fertilizer tank (Fig. 3). The process of filling and discharging the fertilizer disc was simulated and analyzed. It was found that in the process of filling, when the rotation speed of the fertilizer disc is 5 r min^{-1}, the fertilizer particles gather on the fertilizer tank for too long. This intensifies the wear caused by fertilizer particles to the housing of the fertilizer discharging device and increases the rate of fertilizer particle breakage. As the rotation speed of the fertilizer disc increases, the friction and shear forces of the fertilizer particles are significantly reduced. In the process of discharging fertilizer, when the speed of the discharging disc is 5 r min^{-1}, the rotation angle γ of the fertilizer particles discharged from the fertilizer tank to the lower shell varies in the range of 9–46°. As the rotation speed increases, the rotation angle γ increases. When the speed of the fertilizer disc is 65 r min^{-1}, most of the fertilizer in the fertilizer tank will hit the shell at the end of the fertilizer zone before sliding down the fertilizer mouth along the shell. At this time, the maximum range of variation in turning angle γ is already greater than the

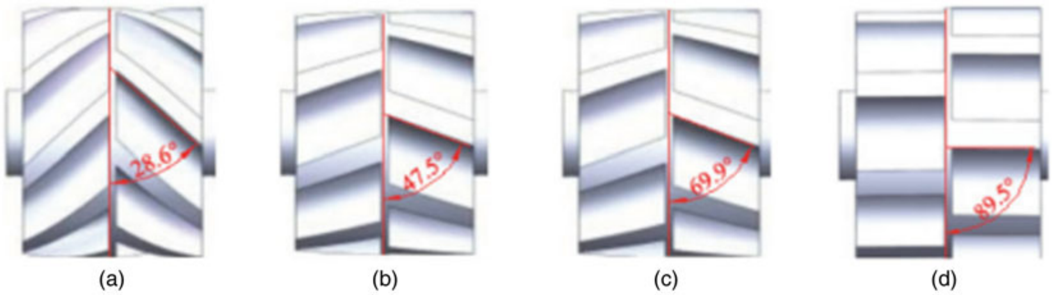

Fig. 5. Angles of helical teeth used in simulations: (a) 28.6°, (b) 47.5°, (c) 69.9°, (d) 89.5°.

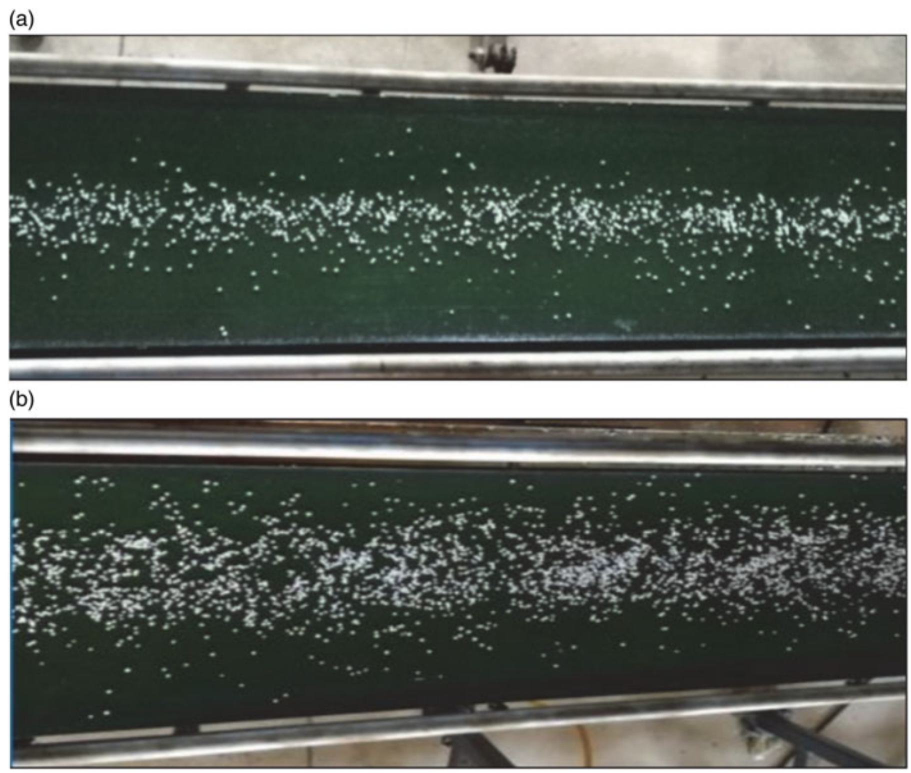

Fig. 6. Fertilizer distribution in laboratory tests with a 30 mm working length and 20 rpm rotational speed for (a) an OGWFA with 47.5° helical teeth, (b) an OGWFA with straight teeth.

central angle corresponding to the fertilizer discharging area, which is not conducive to fertilizer discharge. Therefore, the best working speed of the fertilizer discharging disc is 10–60 r min^{-1}.

Outer groove wheel-type fertilizer discharging devices

Outer groove wheel-type fertilizer discharging devices are the most common fertilizer discharging devices on the market (Fig. 4) (Zuo, 2016). They have a simple structure, are suitable for loose chemical fertilizers and granular compound fertilizers, and have good fluidity. During operation, the grooved wheel (which has a certain shape groove on the surface) rotates with the fertilizer shaft, and the rotating outer groove wheel continuously discharges the fertilizer in the groove, which falls by gravity. At the fertilizer outlet, it flows into the mud ditch opened by the opener through the corrugated pipe. Outer groove wheel-type fertilizer discharging devices can be divided into fixed and mobile types according to whether the grooved wheel can move axially. Among them, the mobile outer groove wheel-type fertilizer discharging device can more easily adjust the rate of application. However, when applying powdery and relatively moist fertilizers, it is prone to clogging and other phenomena.

The shape, outer diameter, number of grooves and speed of the outer sheave are important factors affecting the rate and precision of fertilizer application. The traditional outer grooved-wheel device is mainly equipped with straight grooves, and the particles are discharged from the exit under free-flow condition. More particles are discharged when the grooved wheel turns to the groove, while fewer particles are discharged when the grooved wheel turns to the ridge. This phenomenon is particularly obvious at low speeds. At the same time, during the movement, the particles in the grooved wheel are subjected to a large force, which easily breaks the particles or causes the grooved wheel to get stuck, which affects the precision of fertilization (Arif, 2010). When the outer groove wheel is a spiral groove wheel, as the fertilizer wheel rotates, granular fertilizer is continuously discharged along the rotation direction of the groove, which helps to improve

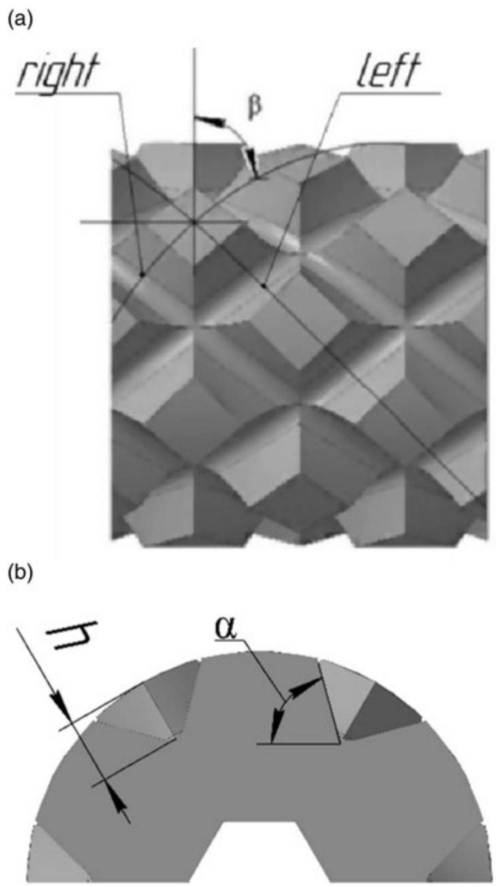

Fig. 7. Parameters of the roller pin: (a) n = number of right and left entry lines, β = angle between the vertical axis and right and left entry lines, (b) h = height of the roller pin and α = angle between the hexagonal polygon and pin inclination.

the uniformity of fertilizer discharge (Leng *et al.*, 2018). Du *et al.* (2020) adopted a staggered spiral tooth design and simulated fertilization performance using a discrete element model (DEM). A spiral angle of 47.5° was considered reasonable for an outer groove wheel fertilizer applicator (OGWFA). A 47.5° spiral tooth has a lower coefficient of variation and a smaller fertilizer distribution width than a straight tooth outer groove wheel fertilizer discharging device (Figs. 5 and 6).

Sugirbay *et al.* (2020) studied a pin-roller device with different α angles, pin heights, β angles and radii between two pins (Figs. 7 and 8). The design evaluated fertilizer distributions under 25 pin roll configurations at three speeds. Indoor experiments showed that different pin roller characteristics have a significant impact on the uniformity of fertilizer distribution and discharge. At all speeds of the device, the flow of the new pin-roll device was not lower than that of the device with the outer groove wheel structure, but the coefficient of variation of the flow of the pin roll was larger than that of the outer groove wheel structure at lower speeds. However, at higher speeds, there was no significant difference in the coefficients of variation of the devices.

The diameter of the outer groove wheel is also an important factor affecting the rate and precision of fertilizer application. When the rate of fertilization is constant, the diameter of the fertilization wheel is too large, the speed and the effective working length are reduced correspondingly and the uniformity of fertilization will decrease. As the diameter of the fertilizer wheel

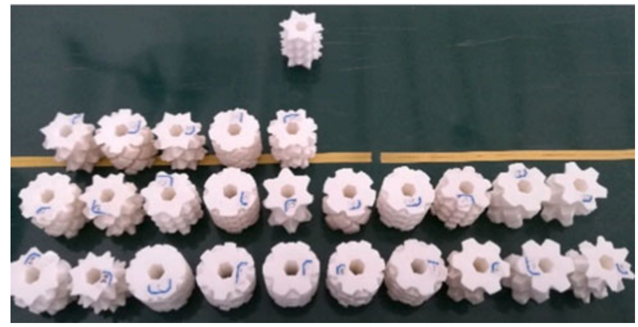

Fig. 8. Twenty-five 3D-printed pin-rollers with different parameters.

becomes smaller, the number of uniformly distributed slots on it will decrease accordingly. To meet a certain range of fertilizer application adjustment, the speed of the fertilizer wheel must be increased. When the rotation speed of the fertilizer wheel is too large, not only is the wear rate of granular fertilizer increased, the time taken for the fertilizer wheel to pass through the fertilizer filling area will be shortened, and the granular fertilizer filling factor in the groove will decrease accordingly, affecting the stability of fertilization. However, some studies have pointed out that higher fertilizer wheel rotation speeds improve the uniformity of fertilization (Jin-Feng *et al.*, 2018). Sun *et al.* (2020) used the rate of fertilization as an indicator to explore the best working parameters for an OGWFA (Figs. 9–11). Simulation and experimental results show that under static and dynamic conditions, the force on the fertilizer particles first decreases and then increases with increases in the helix angle. Under static conditions, the discharge speed of the fertilizer particles first increases and then decreases with increases in the helix angle, and then fluctuates within a small range. Under dynamic conditions, the discharge speed of the fertilizer particles first decreases and then increases with increases in the helix angle, and finally fluctuates in a small range. The interaction between the radius of the outer groove wheel and its speed has a significant effect on the rate of fertilizer. The groove radius *vs* speed, the groove radius and the inclination angle of the fertilizer feeder have significant effects on the coefficient of variation of fertilizer application. The optimal working parameters are: groove radius = 13.5 mm, helix angle = 62°, rotation speed = 29.4 r $\min^{-1}$ and fertilizer feeder inclination angle = 5°.

Jin-Feng *et al.* (2018) analyzed a theoretical fertilizer supply model for an outer groove wheel. A cross-section of the grooved section of an outer groove wheel-type fertilizer discharging wheel is shown in Figure 12. The groove section has an 'L' profile and is composed of a normal line segment, a tangential line segment and a circular arc with a central angle of 90°. The radius r of the arc is greater than the radius of the granular fertilizer. The filling cross-sectional area S_0 of a single 'L'-shaped fertilizer groove is the sum of the spherical cap area S_1, the right-angle trapezoidal area S_2, the spherical cap area S_3, the triangular area S_4 and the sector area S_5. The formula is as follows:

$$S_0 = S_1 + S_2 + S_3 + S_4 + S_5 \tag{1}$$

where,

$$S_1 = \frac{\varphi - \psi}{360}\pi R^2 - \frac{1}{2}R^2 \sin(\varphi - \psi)$$

https://doi.org/10.1017/S1742170522000151 Published online by Cambridge University Press

Fig. 9. Helical grooved wheel.

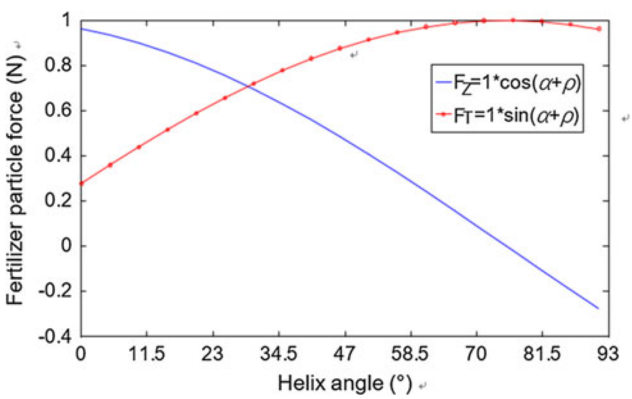

Fig. 10. Variations in circumferential force F_T and axial force F_Z with helix angle.

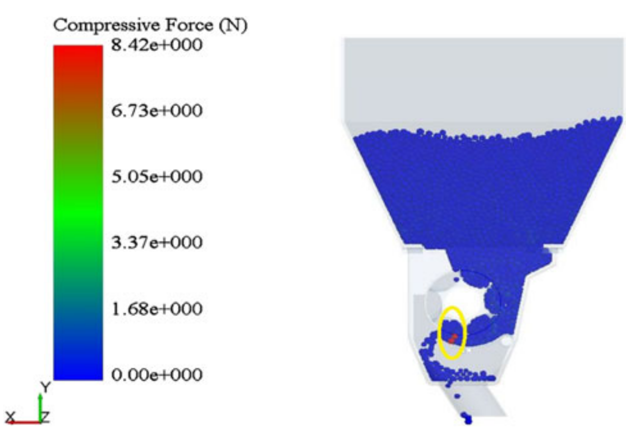

Fig. 11. Position of maximum force.

$$S_2 = \frac{1}{2} r(R \sin \psi - r + q)$$

$$S_3 = \frac{\psi}{360} \pi R^2 - \frac{1}{2} R^2 \sin\psi$$

$$S_4 = \frac{1}{2} pR \sin \psi$$

$$S_5 = \frac{1}{4} \pi r^2$$

where φ, ψ is the central angle (°); q is the tangential line segment length (mm); p is the length of a normal line segment (mm) and r is the circular arc radius (mm).

According to the working process of these devices, when the fertilizer discharging wheel rotates, the granular fertilizer that enters the groove is discharged through the opening under the force of the grooved teeth of the discharging wheel, which is called a *forced layer*. A layer of granular fertilizer with a thickness of C_0 on the outer edge of the fertilizer wheel is intermittently squeezed by other granular fertilizers and the protruding parts of the grooved teeth. It is discharged at a relatively low speed between the outer edge of the fertilizer wheel and the brush, and the discharge is called the *driving layer* (Pan *et al.*, 2016). Then, the amount of fertilizer discharged per turn of the fertilizer wheel is:

$$q_0 = q_1 + q_2 \tag{2}$$

where $q_1 = \lambda\sigma L_0 Z S_0$; $q_2 = 2\pi\sigma R L_0 C_n$, where λ is the filling coefficient of granular fertilizer in the groove; σ is the volume-weight of granular fertilizer (kg m^{-3}); and C_n is the driving layer characteristic coefficient; L_0 is the effective working length of groove.

Screw-type fertilizer discharging devices

Screw fertilizer discharging devices are used in many rice fertilization machines. They have the advantages of a simple structure, closed conveying environment, adjustable conveying volume and stable single-ring conveying volume. They are a forced conveying method (Jiang *et al.*, 2019). However, in the application process, the fertilizer storage space formed between the spiral blade and spiral sleeve differs when the rotation of the end surface of the blade of the fertilizer outlet goes to a different position. Fertilizer particles are differently blocked by spiral blades and spiral sleeves, resulting in pulsation of fertilizer particles and periodic changes in application rate. This restricts their application in fine feeding devices (Anton *et al.*, 2007; Yuan *et al.*, 2020). Therefore, reducing the pulsation phenomenon in screw-type fertilizer mechanisms has become a research focus.

Structural parameters, such as the length and angle of the fertilizer discharge opening, and the pitch and outer diameter of the screw fertilizer discharge device, are important influences on the fertilizer application rate (Fig. 13) (Kretz *et al.*, 2015). Yang *et al.* (2020) studied the influences of the length and angle of the fertilizer opening on the uniformity of fertilizer application at a spiral speed of 30 r min^{-1}. It was found that the primary and secondary factors affecting the performance of the screw fertilizer discharging device were the length and angle of the discharge port. The two have very significant impacts on the stability and uniformity of fertilizer discharge. The best application effect was achieved at a 135° angle and length of 60 mm (Figs. 14 and 15). In addition, the screw conveying mechanism was optimized by adding a double helix structure and leaving an empty pitch.

https://doi.org/10.1017/S1742170522000151 Published online by Cambridge University Press

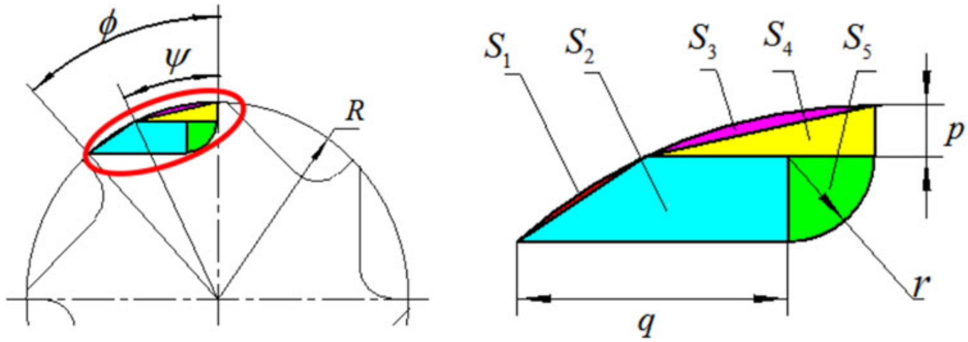

Fig. 12. Schematic diagram of the fertilizer wheel filling area.

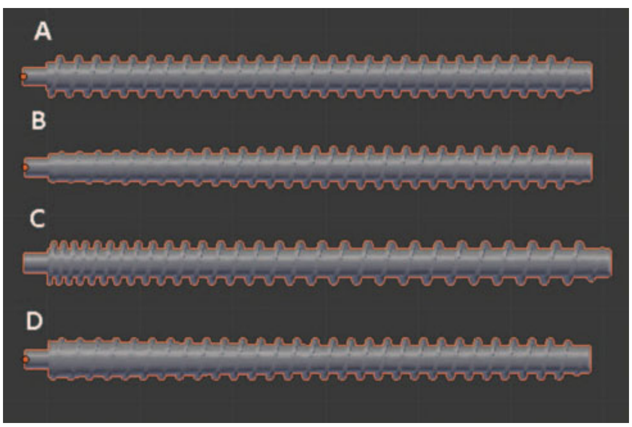

Fig. 13. Different screw shapes for investigating slide-in behavior: (a) reference screw, (b) conical threads, (c) variable thread pitch, (d) variable screw shaft diameter.

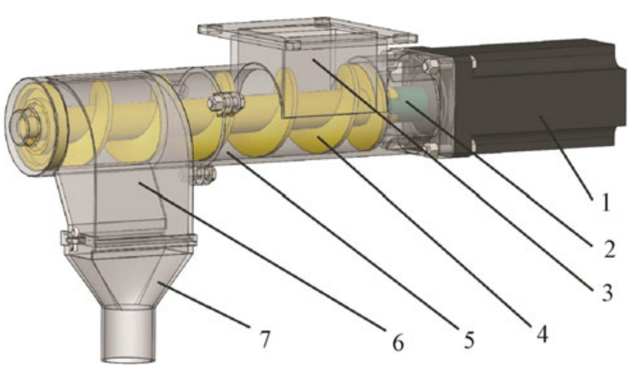

Fig. 14. Schematic diagram of a screw fertilizer discharging device: (1) drive motor, (2) coupling, (3) feeding inlet, (4) screw, (5) screw shell, (6) discharge port, (7) concentrator.

The researchers analyzed the relevant parameters of the two-stage spiral fertilizer device by establishing a mathematical model of the fertilizer discharge volume of the fertilizer discharge screw. It was determined that the device had a good discharging effect and good adaptability to various forms of fertilizer, so that material discharge pulsation was reduced (Chen *et al.*, 2015). However, due to the need for additional devices, it is not conducive to application to small machines (Wang *et al.*, 2005). For unloading speed, it directly depends on the rotating speed of the discharging devices (Camacho-Tamayo *et al.*, 2009), and is directly related to the material's density (Walker *et al.*, 1997). At the same time, it is affected by the particle size, repose angle, bulk density, surface roughness and moisture content of the fertilizer (Grift *et al.*, 1997; Aphale *et al.*, 2003).

In side-deep rice fertilization devices, because the spiral pulsation cycle is quite complicated, reducing the pulsation cycle can reduce the size of the overall pulsation, although it increases the complexity of the system. Therefore, a screw fertilizer discharging device is often combined with other types of discharge devices. A screw fertilizer discharging device uniformly conveys fertilizer to the outer groove wheel or rotary disc discharging device for secondary distribution. Finally, fertilizer is forced to the outlet by pneumatic conveyance or a mechanical device.

Key components of fertilizer conveyance devices

Pneumatic

Pneumatic fertilization devices use positive air pressure to convey auxiliary fertilizer. The fertilizer particles are discharged by the device carried by flowing gas and fall into the grooves drawn by the opener along the direction of the pipeline under the dual action of airflow and own gravity. This method can effectively prevent problems such as poor flow in the fertilizer pipeline caused by deliquescence of fertilizer particles and clogging. This is the key to achieving stable fertilization (Zuo *et al.*, 2016). Pneumatic fertilizer conveying devices are mainly composed of a fan, a fan speed switch, an air supply pipe, a venturi pipe (Fig. 16) and a corrugated conveying pipe. Among them, the venturi pipe is a key component of the air delivery system, and includes a fertilizer inlet, air inlet, contraction section, throat, diffuser and air outlet. The lower fertilizer port, air supply pipe and fertilizer pipe of the discharging device are respectively connected with three ports in the venturi pipe. During operation, the air flow from the fan at the front end of the air delivery system passes through the inlet cylindrical section and through the cylindrical throat at high speed. Negative pressure is formed at the feed inlet, so that there is no gas leakage from the feed port (Hu, 2013). The fertilizer particles are smoothly dropped into the fertilizer pipeline and fully mixed with the air flow, and then transported through the pipeline to the groove drawn to the side of the seedlings.

Pneumatic fertilizer-conveying devices mix granular fertilizer with high-speed airflow to form a gas–solid mixed flow. In-depth research on the pneumatic conveyance of solid particles has been made, with simulations considering particle velocity and acceleration, as well as the deposition characteristics of solid particles in the conveyance pipeline (Kumar and Durairaj, 2000; Li *et al.*, 2005; Wang *et al.*, 2017; Yatskui *et al.*, 2017; Tripathi

https://doi.org/10.1017/S1742170522000151 Published online by Cambridge University Press

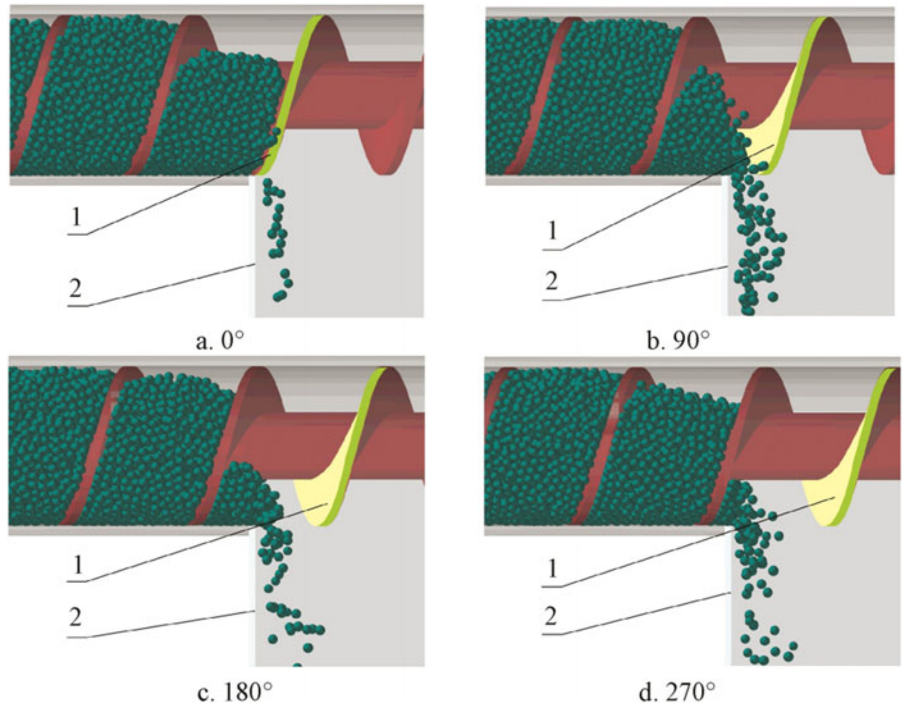

Fig. 15. Simulation of transient fertilizer discharge with the screw blade at different phase angles: (1) screw, (2) spiral casing end face.

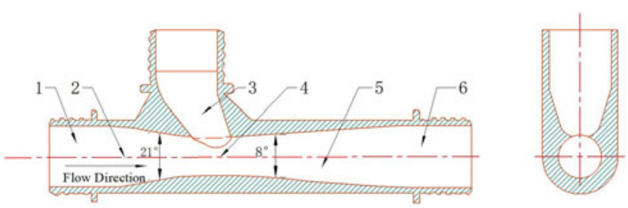

Fig. 16. Venturi structural diagram: (1) inlet cylindrical section, (2) conical contraction section, (3) feed inlet, (4) cylindrical throat, (5) conical diffusion section, (6) export cylinder section.

et al., 2018). In actual operations, the speed of the fan is often fixed to maintain good continuity and stability of fertilization at the minimum or maximum rates. Previous studies have shown that when the wind speed from the fan is 18–35 m s^{-1}, the fertilizer particles are evenly distributed, which is beneficial to the accuracy and uniformity of fertilization (Li-Wei *et al.*, 2018; Yang *et al.*, 2019). In terms of fertilizer materials, Wen *et al.* (2020) tested three granular fertilizers—large urea, diammonium phosphate and potassium sulfate (Fig. 17)—and used the Lagrangian model in a gas–solid two-phase-flow coupled simulation. It was found that the suspension speed of the particle group decreases with increases in the volume fraction. At different volume fractions of particle fertilizer, the relative error between the simulation results and test results was approximately constant. This result provides a basis for the design of air-fed fertilizer conveyance mechanisms.

Yang *et al.* (2019) coupled DEM-computational fluid dynamics simulation to perform numerical analysis of particle movement in a pneumatic centralized fertilizer distribution device (Figs 18–20). By studying the influence of the cone angle of the screw cap and the diameter of the corrugated pipe of the centralized fertilizer distribution conveying device on the air pressure, wind speed and movement characteristics of the fertilizer particles, the optimal structural parameters were determined. Based on this structure, the influences of inlet wind speed and fertilization rate on the uniformity of fertilizer distribution were further studied. It was found that the cone angle of the distributor screw cap and the diameter of the bellows significantly affect the movement of fertilizer particles, airflow velocity and the pressure field distribution. At a distributor screw cap cone angle of 120° and corrugated pipe diameter of 80 mm, the fluidity and uniformity of the two-phase airflow and fertilizer in the fertilizer separation device were optimal.

Mechanical forced

Mechanical forced fertilizer conveying devices usually use a screw conveyor or a spiral steel wire to convey fertilizer. Fertilizer particles discharged from the device fall into the groove drawn by the opener along the direction of the pipeline under the combined action of screw thrust and gravity. The whole process is usually divided into three stages (Wei *et al.*, 2020). As shown in Figure 21, in the filling stage, with rotation of the screw conveyor, the flow of fertilizer particles does not accumulate, so the fertilizer enters the screw conveyor under its own gravity and is brought into the components. In the conveying stage, the fertilizer is forcedly pushed by the spiral surface of the screw conveyor and moved to the bottom of the tee. The lower surface of the spiral surface of the screw conveyor does not form a large effective shear force area, and the effective friction area is relatively small. In the discharging stage, the fertilizer particles are forced out of the screw conveyor under the thrust of the lower surface of the screw conveyor. The force on the fertilizer mainly comes from the lower surface of the screw conveyor. Structural parameters such as the diameter, speed and pitch of the screw-type forced fertilizer delivery device are important influences on application rate. Wei *et al.* (2020) considered that the influences on the fertilizer delivery performance index, from large to small, are the speed, pitch and diameter, and established regression equations

https://doi.org/10.1017/S1742170522000151 Published online by Cambridge University Press

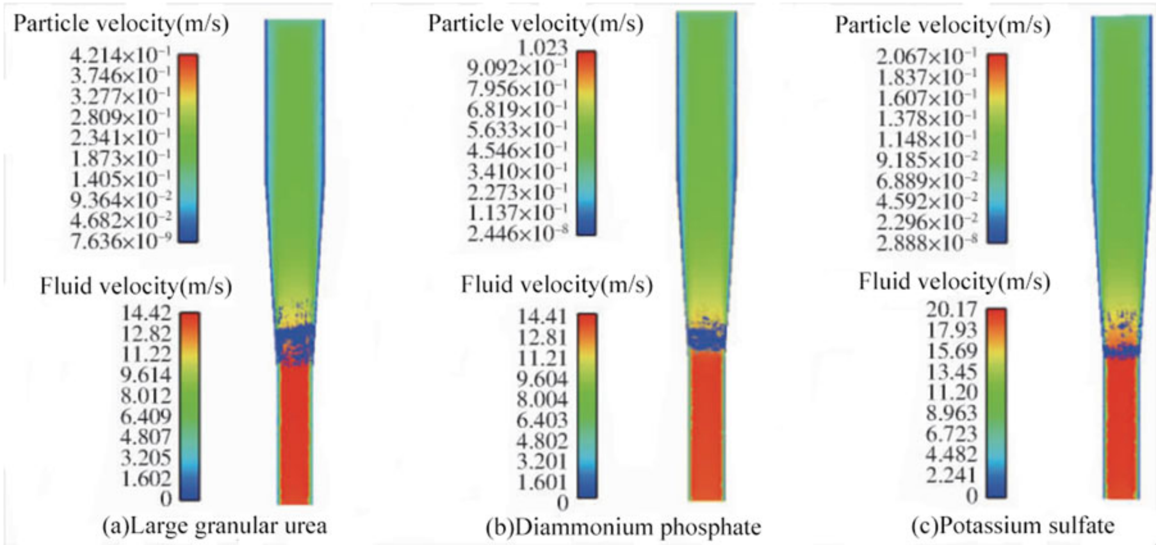

Fig. 17. Suspension position and velocity flow field distribution of different fertilizer particle groups.

between the fertilizer delivery performance index and each factor. The optimal combination of working parameters was determined to be a screw conveyor speed of 120.09 r min^{-1}, diameter of 23.90 mm and pitch of 21.54 mm. Unfortunately, there is still little research on the mechanism of screw-type forced fertilizer conveying devices, as non-forced types are the usual focus (Fig. 22).

Sensors

In order to improve the fertilizer utilization efficiency of rice side-deep fertilization operation machinery, variable fertilization technology is widely used. Currently, variable fertilization is mainly achieved in two ways, based on (1) fertilization decision data of a variable fertilization prescription map (Bacenetti *et al.*, 2020), or (2) fertilization data calculated by real-time sensors (Table 3) (Wu and Song, 2021). The operating machinery applies a specified amount of fertilizer within a certain area based on the fertilization data (Zhao *et al.*, 2003; Fu *et al.*, 2008). Variable-rate fertilization technology has been widely used in dryland agricultural production in European and American countries and has been commercialized (Birrell and Hummel, 2001; Burks *et al.*, 2005; Kodaira and Shibusawa, 2013; Pennock *et al.*, 2014; Rudolph *et al.*, 2016). For example, Ag-Chem has conducted a lot of research on variable fertilization and has developed many mature products. Their variable fertilization system can carry out variable fertilization control of solid and liquid fertilizers. At the same time, variable fertilization can be controlled independently for different fertilizers according to a pre-loaded variable fertilization decision prescription map. The ACCU-PLANT programmable planter fertilization control system produced in Iowa, USA, is mainly composed of a hydraulic transmission system, a ground speed sensor and a microprocessor. The fertilizer discharging device is driven by a hydraulic motor and the controller mainly adjusts the fertilization amount by changing the motor speed to achieve variable fertilization. The ZA-M series suspended variable spreader and ZA-B series traction variable spreader developed by Amazone (Germany) are equipped with Amazon ISOBUS service terminal communication equipment and a variety of agricultural sensors. It can collect crop growth characteristics in real-time, quickly calculate the suitable fertilization amount for crop growth in a unit area and control the working speed and width of the centrifugal fertilizing disc through an independent hydraulic drive device to achieve precise variable fertilization. In addition, there are the Flexi Soil variable fertilization planters from the Case Company, USA (Sudduth *et al.*, 2001; Alchanatis *et al.*, 2005; Kim *et al.*, 2008; Cui *et al.*, 2010; Anh *et al.*, 2014) (Fig. 22).

In recent years, variable fertilization technology has also received increasing attention in Asia, and precision agriculture has developed rapidly in China, Japan, South Korea and other countries. The JKB series self-propelled paddy field variable spraying fertilizer applicator produced by Japan Iseki Agricultural Machinery Co., Ltd. integrates variable spraying and fertilizer spreading systems. It performs real-time collection of information on soil nutrients and crop characteristics through a variety of agricultural sensors, and adjusts the amounts of spray and fertilizer through a controller, making it suitable for variable fertilization operations in each rice growing period. Shi *et al.* (2018) and Zuo (2016) developed a variable rice fertilizer applicator using speed sensors, global positioning system), near-Earth spectrum detection technology and fuzzy PID control technology. The fertilization amount is adjusted in real-time according to the sensor information to carry out precise side-deep fertilization and improve fertilization uniformity. However, its actual application effect still needs further verification.

Japan has done unique research on variable side-deep fertilization technology for rice, especially for use in small-scale plots. However, current research on the variable fertilization of rice mainly focuses on the growth of rice seedlings and, due to the constraints of its sensors, this technology has not been widely applied.

Impact of side-deep fertilization on rice and soil

The rational use of side-deep fertilization technology is key to improving fertilizer utilization efficiency and improving rice quality and yield. Therefore, understanding its effects on rice, fertilizer and soil is extremely important for its application and promotion. Next, this study elaborates on these effects as well as the influences on soil microorganisms.

https://doi.org/10.1017/S1742170522000151 Published online by Cambridge University Press

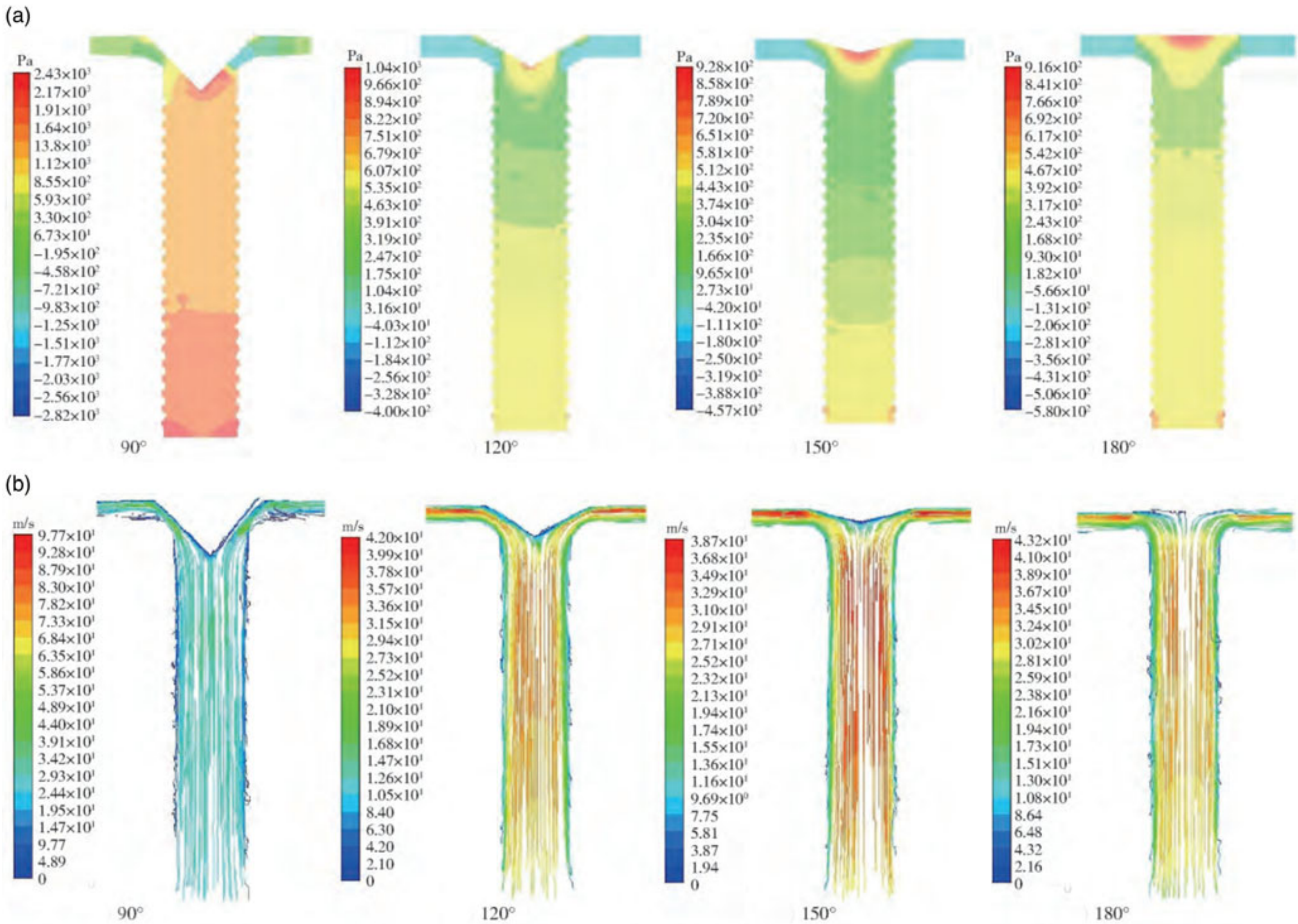

Fig. 18. Pressure cloud charts and velocity distributions of fertilizer distribution devices with different screwing caps: (a) pressure cloud charts, (b) velocity distributions.

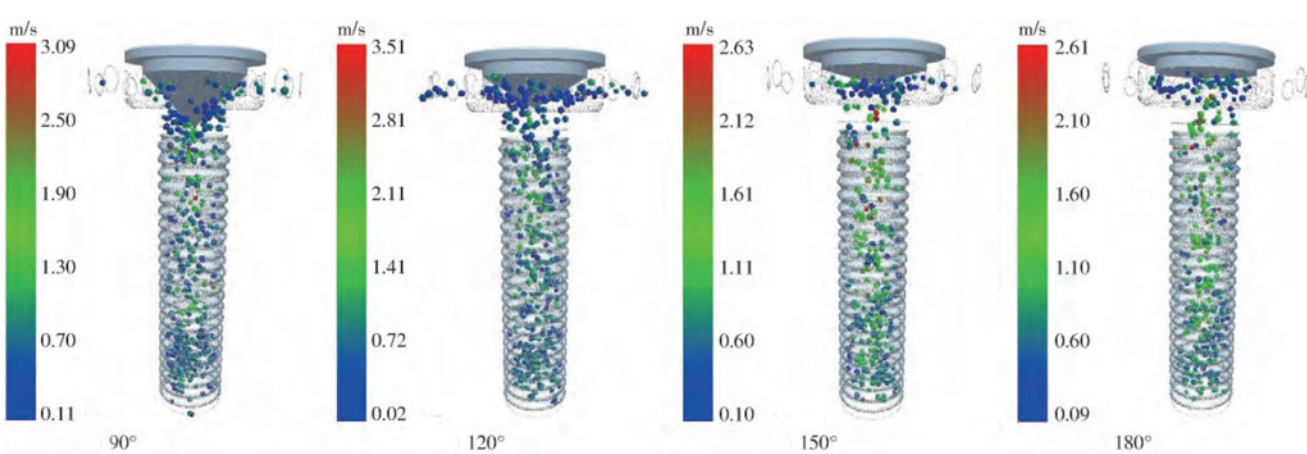

Fig. 19. Distributions of fertilizer particles in fertilizer distribution devices with different screwing caps.

Effects of side-deep fertilization on rice growth and development

Compared with conventional fertilization methods, side-deep fertilization can increase the nitrogen concentration at the roots and meet the nutrient requirements of the rice seedling stage. At the same time, side-deep fertilization provides a kind of asymmetric partial fertilization of the rhizosphere of crop seedlings. Nutrients are accurately delivered to the root zone via machinery, which increases the concentration of nitrogen fertilizer by about five times compared with that of the surface layer. However,

https://doi.org/10.1017/S1742170522000151 Published online by Cambridge University Press

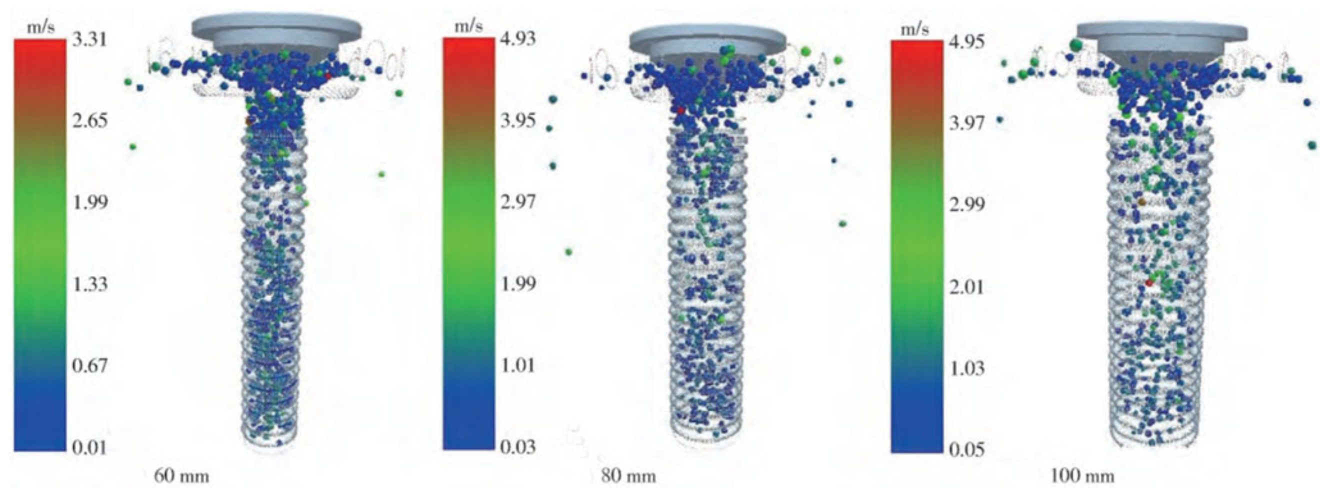

Fig. 20. Distributions of fertilizer particles in fertilizer distribution devices with different bellows.

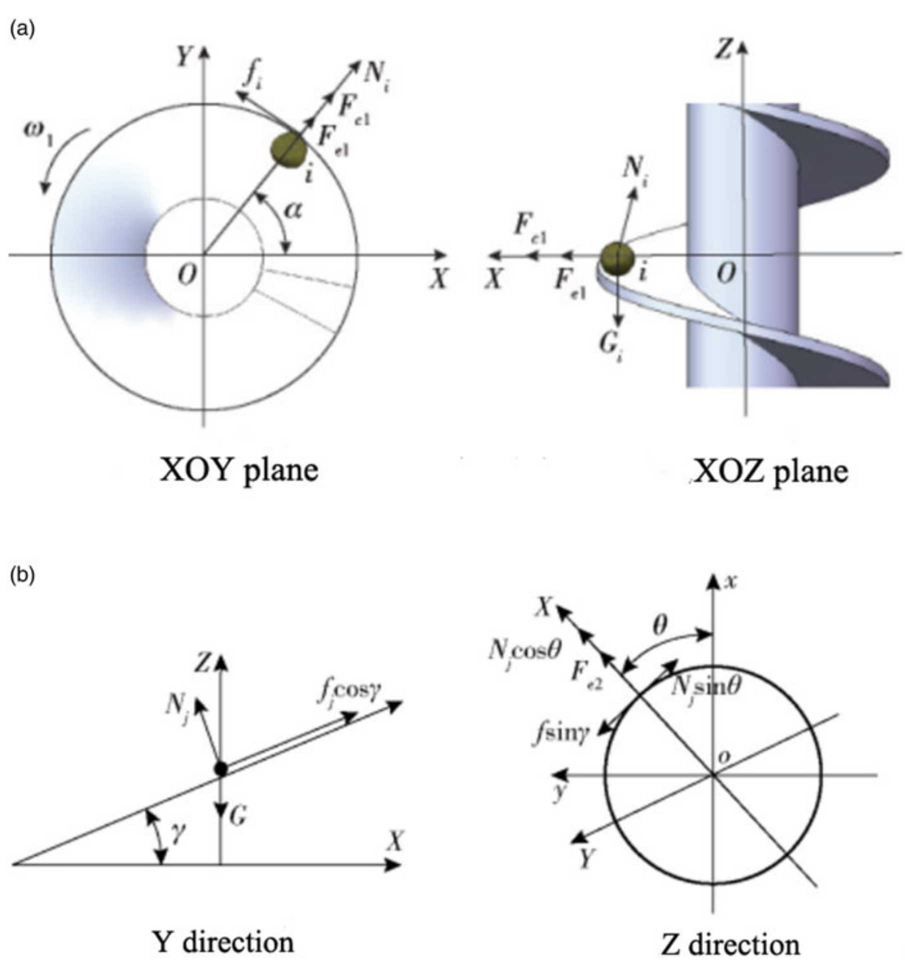

Fig. 21. Force analysis of fertilizer particles during forced fertilizer delivery: (a) establishment of mechanical forced fertilizer component: (1) bearing, (2) screw conveyor, (3) opener, (4) tee, (b) initial force analysis of fertilizer particles, (c) force analysis of fertilizer particle, (d) force analysis at moment of fertilizer particle sliding.

this local nutrient supply will cause an uneven distribution of soil nutrients. Wang *et al.* (2013), Jing *et al.* (2013), Li *et al.* (2012) and others believe that the local nutrient supply is conducive to root proliferation and can change the root morphology by increasing the root length, lateral root density and fine root ratio. It has a stronger effect on crop growth and nutrient absorption in the early growth period than in the later period. However, a local nutrient supply may cause uneven rice growth. Wang *et al.* (2002) studied the effects of NO_3^- on the development of lateral rice roots and their nitrogen uptake through vermiculite culture experiments under dry conditions. They found that a local supply of NO_3^- promotes the growth of lateral rice roots. In addition, side-deep fertilization promotes the absorption of fertilizers under adverse conditions, such as low temperatures, compared

https://doi.org/10.1017/S1742170522000151 Published online by Cambridge University Press

Table 3. Comparison of the advantages and disadvantages of different sensors

Sensor type	Advantage	Disadvantage
Camera		
Monocular camera	Simple operation and low cost	Unable to collect depth information
Binocular camera	Can obtain the depth information of the target in moving and static states	The calibration and calculation process is relatively complicated and the amount of calculation is large
Depth camera	Color and depth information of the object can be obtained, data collection speed is fast and the data volume is abundant	Vulnerable to field angle and resolution effects
Lidar		
2D Lidar	Suitable for plane information collection	Perceived data are sparse and difficult to image
3D Lidar	Perceived data have the height and distance information of the target, can restore the shape of the object and can work around the clock	Expensive and susceptible to weather such as rain, snow, haze, etc.
Inertial measurement unit (IMU)	Collects target acceleration and attitude angle information	Prone to accumulated errors
Millimetre-wave radar	Strong penetrating power in rain, snow, haze, etc.	Low data accuracy, the calculation time is long for multi-chirp
Ultrasonic radar	Low energy consumption, long propagation distance in the medium, low price	The transmission speed is extremely susceptible to weather and is relatively slow
Infrared thermal imager	Information experience is more intuitive, not affected by electromagnetics, has a relatively long operating distance and all-weather environmental perception	High cost, low image resolution and low information contrast

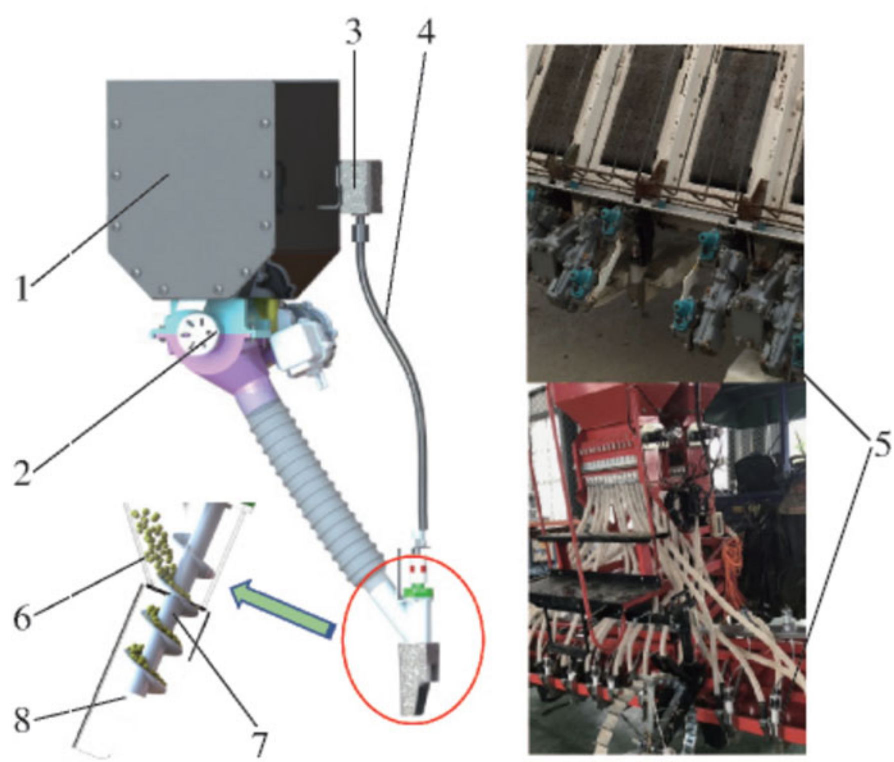

Fig. 22. Structural diagram of mechanical forced fertilizer components: (1) Fertilizer box, (2) Electric fertilizer discharging device, (3) Drive motor, (4) Flexible shaft, (5) Forced fertilizer discharging parts, (6) Tee pipe, (7) Screw conveyor, (8) Ditch opener.

with conventional fertilization. The maximum tillering stage of rice appears earlier and the number of divisions occurring within 30 days of transplanting is as much as 30% greater than that of conventional fertilization. It can increase low node tillers, reduce the number of ineffective tillers, advance the heading date and ensure the safe maturity of rice. If fast-acting fertilizer is used for side-deep fertilization, the nitrogen concentration in the soil layer will be reduced 30 days after rice transplanting, avoiding lodging caused by overgrowth, fully reducing ineffective rice tillers, and promoting early rice development (Zhu *et al.*,

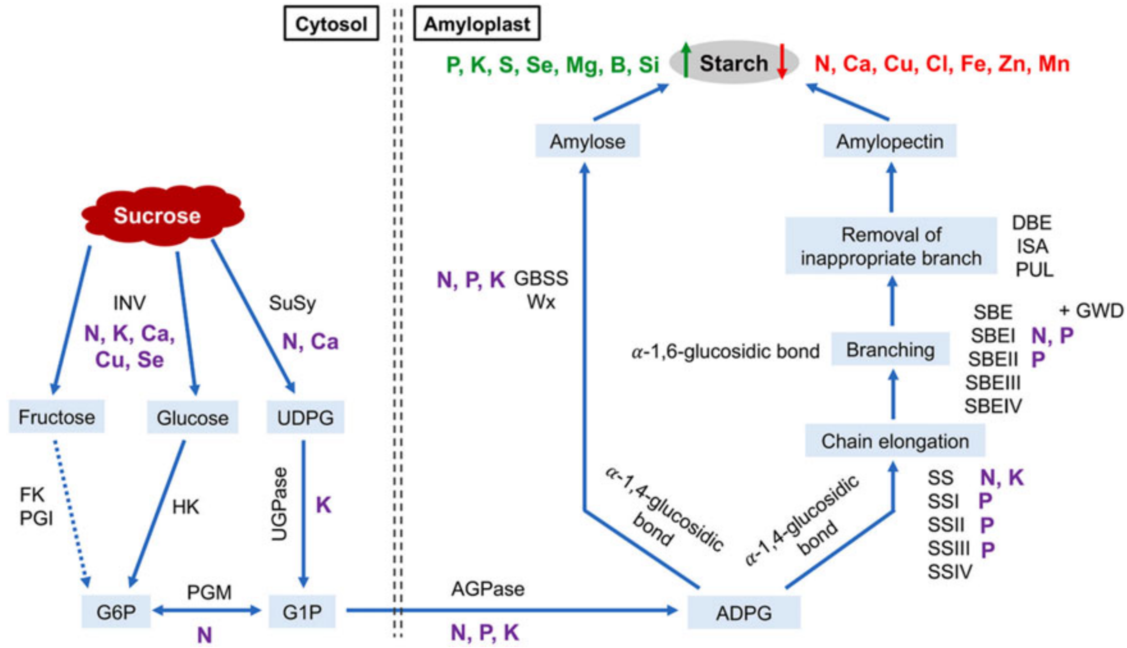

Fig. 23. Roles of plant nutrients on the biosynthesis pathway of storage starch in amyloplasts. Sucrose is the fundamental carbon donor to glucose-1-phosphate (G1P) for storage starch synthesis. In cytosol, sucrose is primarily metabolized by invertase (INV), sucrose synthase (SuSy), fructokinase (FK), hexokinase (HK) and UDP-glucose pyrophosphorylase (UGPase). In amyloplasts, the generated starch-synthesizing precursor ADPG is used to form amylose synthesized by the granule-bound starch synthase (GBSS) enzyme coded by the so-called waxy (Wx) locus. This forms amylopectin via synthesis with soluble starch synthases (SSs) in concert with starch branching enzymes (SBEs) and starch debranching enzymes (DBEs) such as isoamylase-type starch-debranching enzyme (ISA) and pullulanase (PUL), as well as the starch phosphorylating enzyme glucan water dikinase (GWD). The green up-arrow indicates that the starch content increases with increasing application of the plant nutrients marked in green. The red down-arrow indicates that the starch content decreases with increasing application of the plant nutrients marked in red. Plant nutrients marked in purple are directly involved in the regulation of corresponding enzyme activities.

2019*b*). If side-deep fertilization is done with a controlled-release fertilizer, nutrients can be released slowly over the entire growth period, and can release nutrients at a suitable rate for the rice plant's requirements (Xiao-Dan *et al.*, 2021). But there are also studies that point out (Lyu *et al.*, 2021), since a controlled-release fertilizer has a slow release of nutrients in the early stage of rice growth, it is not conducive to rice tillering. A mixed treatment of slow-release nitrogen fertilizer and urea can effectively increase rice yield and nitrogen fertilizer utilization, and has the best economic benefits.

Relationship between side-deep fertilization and rice yield

The yield of rice is composed of four parts: the number of panicles, the number of spikelets per panicle, the seed setting rate and the thousand-grain weight (Pan *et al.*, 2016). Predecessors agree that increasing the number of spikelets in the population (number of panicles × number of spikelets per panicle) is the key to increasing rice yield while ensuring the stability of the seed setting rate and thousand-grain weight (Huda *et al.*, 2016; Xie *et al.*, 2019). Reasonable fertilization methods can promote the formation of effective tillers, so that rice has a higher population of spikelets, thereby forming a more reasonable population (Zhang *et al.*, 2010). Compared with traditional fertilization methods, side-deep fertilization can promote rice tillering and reduce the production of ineffective tillers, ultimately increasing the number of panicle per square meter and the yield (Yang *et al.*, 2006). Compared with surface application, deep layer fertilization can accurately transport nutrients to the roots, thereby reducing nitrogen losses caused by ammonia volatilization and surface runoff (this is the most important mechanism of nitrogen loss in low yield areas of rice) (Vibhu *et al.*, 2008; Roberts *et al.*, 2012; Atique-ur *et al.*, 2014). This gives rice seedlings sufficient nutrients in the early growth stage, thereby promoting early and rapid growth of rice tillers and increasing yield (Wu *et al.*, 2017). Huang (2021) studied the impacts of side-deep fertilization methods on rice yield and found that it increases yield by producing more panicle and population spikelets. The highest yield was obtained with a 70% basal fertilizer side-deep application + 30% panicle fertilizer because this treatment provides a topdressing panicle fertilizer during the top three-leaf period. In the top three-leaf stage, rice is in the young panicle differentiation stage. Adding panicle fertilizer during this stage prevents the leaves from premature aging, promotes the normal metabolism of leaves during the filling stage (Ishfaq *et al.*, 2021) and ensures that the rice has high source-sink activity (Zhu *et al.*, 2020). Moreover, it can also protect the tillers and increase the panicle, thereby increasing the number of panicle and the rate of panicle formation. Increasing spike fertilization can also promote the differentiation of spikelets and reduce the degradation of spikelets, thereby increasing the number of spikelets in the population, increasing the seed setting rate and thousand-grain weight and, ultimately, increasing yield (Ke *et al.*, 2014; Liu *et al.*, 2015). Treatment with 70% basal fertilizer side-deep application + 30% panicle fertilizer can significantly increase the nitrogen content in the root area of rice seedlings in the early growth stage so that the rice has enough nutrients to obtain a larger population, thereby increasing yield (Ding *et al.*, 2003). Zhu *et al.* (2019*a*) and Alimate *et al.* (2015) also showed that side-deep fertilization can increase yield, mainly because it increases the number of effective panicles and the total number of spikelets. This trend was shown in rice in different seasons. In the panicle differentiation stage and full panicle stage, nitrogen accumulation, SPAD value and dry matter accumulation were significantly higher with controlled-release fertilizer combined with side-deep fertilization. This combination is considered effective in increasing rice yield and nitrogen utilization.

Relationship between side-deep fertilization and rice quality

The main factors affecting the cooking and eating qualities of rice are the amylose and protein contents, which are mainly controlled by genetics. However, as shown in Figure 23, starch content is also greatly affected by external environmental factors such as nutrients (Zhang *et al*., 2021). In particular, the application of nitrogen fertilizer has an important role in promoting rice quality (Ji *et al*., 2011), it can increase the protein content or change the amylose content in the rice grain (Parkash *et al*., 2002; Champagne *et al*., 2007). Studies have shown that surface fertilization results in nutrient losses and low protein contents, which reduce rice yield. Therefore, surface fertilization is not the best fertilization method for high-quality rice production. Side-deep fertilization provides effective nutrients to the rice root system and promotes early development, while late top dressing promotes the establishment of a quality framework. At the same time, side-deep fertilization can reduce diseases and insect pests, and produce good-quality rice (Wopereis-Pura *et al*., 2005; Liu *et al*., 2014). According to related measurements, the polished rice rate and brown rice rate can be increased by 2.5 and 3.2%, respectively, and the cooking and eating values can be increased by 10% compared with conventional fertilization. Compared with conventional nitrogen fertilizer, the one-time application of an equivalent amount of slow/controlled-release compound fertilizer not only increases the rice heading rate and setback but also helps reduce the chalky grain rate (Yu *et al*., 2016). However, in the cases of mixed application of slow/controlled-release and conventional nitrogen fertilizers, or one-time basal application of slow/controlled-release fertilizer, there is no significant change in processing quality compared with conventional nitrogen fertilization for a given nitrogen content. The amylose content and gel consistency do not increase significantly but the appearance quality of rice grains is reduced to a certain extent. In terms of nutritional quality, the crude protein content is significantly increased and the ratio of gluten and gluten/alcohol soluble protein increases the most (Wei *et al*., 2018). After further studying the rice quality of grains in different parts of the panicle, it was found that, compared with the equivalent amount of conventional nitrogen fertilizer, one-time basal application of resin-coated slow/controlled-release nitrogen fertilizer reduces the chalkiness degree and chalky grain percentage of the upper panicle by 31.85 and 24.67%, respectively, while the milled rice rate of middle and lower panicles increases by 5.15% (Wu *et al*., 2018). In terms of starch viscosity, at the same amount of nitrogen, mixed application of slow/controlled-release and conventional nitrogen fertilizers results in lower setback value than several applications of conventional nitrogen fertilizer, and other indicators such as final viscosity and disintegration were higher (Yi *et al*., 2013). This shows that slow and controlled-release nitrogen fertilizer improves rice eating quality more than conventional nitrogen fertilizer, but the specific effect is dependent on the fertilization mode.

Side-deep fertilization and fertilizer utilization efficiency by rice

After fertilizer is applied to the soil, controlled by the soil's physiochemical and biological conditions, part of it is absorbed by rice plants, part is fixed by the soil, and most of it is lost through volatilization, runoff and leakage (Savin *et al*., 2021). Side-deep fertilization uses machinery to accurately deliver nutrients to the root zone, so that the rice seedlings and fertilizers are separated to a certain extent, reducing fertilizer damage to the roots and pollution of the local water system (Savant and Stangel, 1990). It also reduces runoff, leakage and volatilization losses, regulates soil nitrogen metabolism enzyme activity, promotes the growth of nitrogen metabolism microorganisms and improves fertilizer nitrogen utilization efficiency (Kargbo *et al*., 2016; Min *et al*., 2017; Yao *et al*., 2017). On the other hand, the amount of fertilization directly affects the fertilizer utilization efficiency by affecting the concentration of ammonium nitrogen in the field water. Suitable fertilizers can be absorbed by plants (Tian *et al*., 2001) and excessive application of nitrogen fertilizers will lead to nitrogen loss. Generally, the greater the nitrogen application, the greater the ammonia loss (Lin *et al*., 2012, 2017). Nitrogen application methods include surface application (spreading), deep application (spreading and then covering the soil) and deep application of granular fertilizer. Studies have shown that there are differences between the ammonia losses of different fertilization methods. Generally, there are greater losses with surface application than with other methods, while ammonia volatilization losses are relatively low with deep application of granular fertilizer. The amount of ammonia volatilization under different fertilization methods is ranked surface application > mixed application > deep application > deep application of granular fertilizer (Xu *et al*., 1993; Maona *et al*., 2018). Liu *et al*. (2015) found that, compared with surface application, deep application of nitrogen fertilizer significantly reduced the pH of the field water by 2–4%, and the concentration of ammonium nitrogen was reduced by 29–98%, thereby significantly reducing NH_3 volatilization by 20–45%. It should be noted that soil NH_3 losses are more sensitive to the fertilization depth. This is mainly because after deep application of nitrogen fertilizer, NH_4^+-N is adsorbed by the soil as it diffuses in it, thereby reducing the NH_4^+-N concentration in the soil (Yao *et al*., 2018a). Deep application reduces contact between the fertilizer and air, promotes root length density (Singh *et al*., 1976), shortens the time taken for nutrients to move to the root system, increases the absorption and utilization of nitrogen by rice, ultimately reducing NH_3 loss in rice fields (Yao *et al*., 2018*b*; Drescher *et al*., 2021). In addition, Rychel *et al*. (2020) and Qi *et al*. (2012) found that increasing fertilizer placement depth may be an effective method for keeping plant available N over longer periods, and found that delaying the nitrogen fertilization period can reduce ammonia volatilization. Zhu *et al*. (2019c) reported that, compared with artificial spreading, side-deep fertilization can significantly improve nitrogen utilization efficiency. The N uptake by stems-sheaths and leaves and the apparent amount of N translocated in stems-sheaths and leaves (TNT) were significantly higher in a CRUM treatment (controlled-release urea + side-deep fertilization) than in other N application treatments (CUB—manual surface broadcast of urea; CUM—mechanized side-deep placement of urea; CRUB—manual surface broadcast of controlled-release urea) from the heading stage to the maturity stage. In addition, Zhao *et al*. (2021) performed surface and deep fertilization treatments

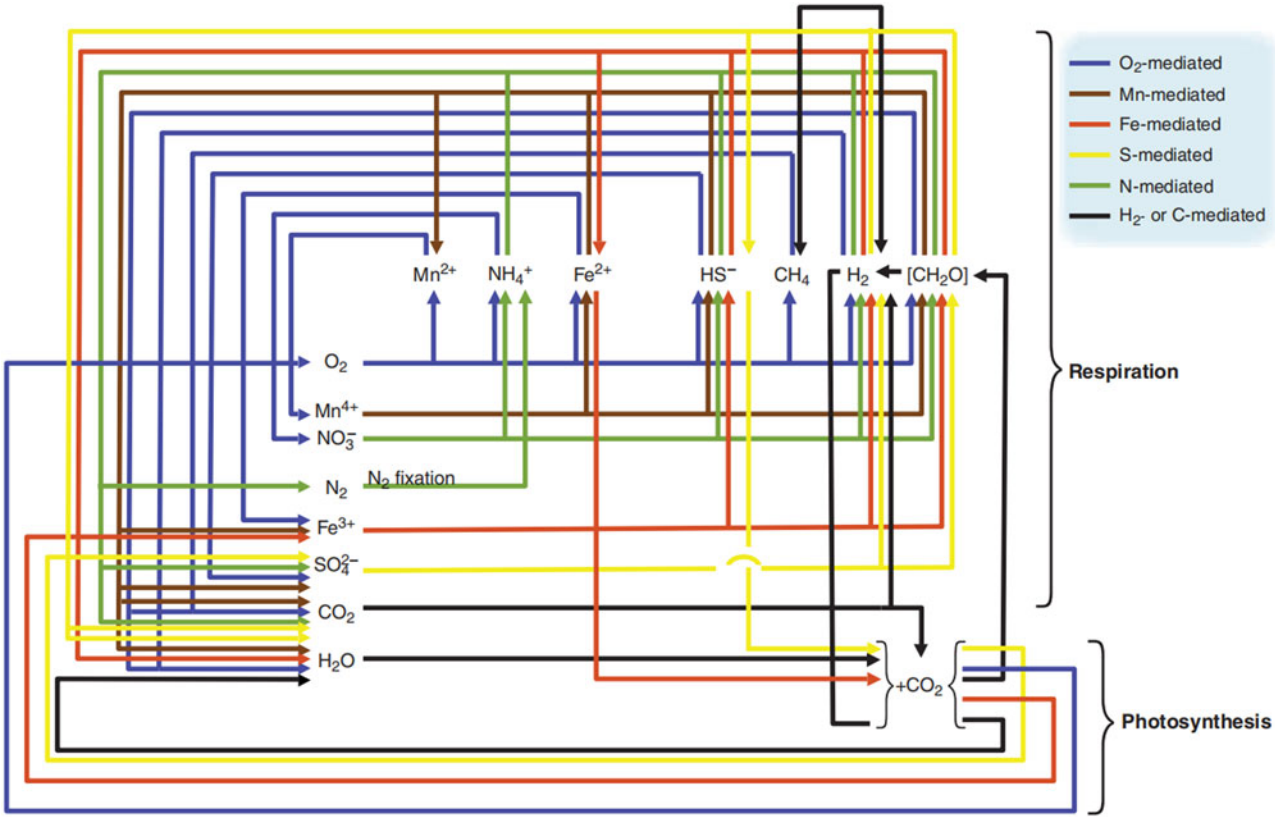

Fig. 24 Schematic diagram of microbial-mediated elemental coupling cycle.

under light and dark conditions. They found that surface fertilization under light conditions promoted the development of periphytic biofilms, while deep fertilization under dark conditions inhibited their development. The development of periphytic biofilms increased the pH and dissolved oxygen levels in the overlying water. Surface fertilization resulted in high N concentrations in the overlying water and topsoil layers, which enhanced NH_3 volatilization and nitrification–denitrification but inhibited N fixation. The presence of periphytic biofilms in paddy fields increased N losses by 3.10–7.11%. Therefore, deep fertilization is an effective way to inhibit the development of periphytic biofilms in rice systems and has the potential to improve overall nitrogen utilization efficiency. Comprehensive analysis shows that the combination of controlled-release and side-deep fertilization can effectively reduce nitrogen losses in paddy fields while increasing the nitrogen utilization rate and rice yield.

Effect of side-deep fertilization on soil microorganisms

Under natural conditions, the circulation of soil elements maintains a dynamic balance. In intensive farming ecosystems, fertilization is an important way to quickly replenish soil nutrients. Both organic and chemical fertilizers can provide nutrients for crops and improve the soil environment (Yang *et al.*, 2018). Soil microorganisms can quickly respond to changes in the soil environment. As shown in Figure 24, the nutrient cycling process mediated by microorganisms is coupled and integral (Falkowski *et al.*, 2008). In terms of biological elemental composition, nitrogen is an important element of cell proteins and other substances. Intake of nitrogen is necessary for the construction and activity of enzymes. Phosphorus is mainly a constituent element of lipids, nucleic acids, ATP and other substances and plays an important role in various forms of metabolism (carbon metabolism, protein metabolism and fat metabolism). Microbial metabolism requires many elements, such as nitrogen and phosphorus. The oxidation of nitrogen, iron, sulfur, manganese and other elements can also provide energy for microorganisms and promote the accumulation of soil nutrients. Therefore, soil microorganisms are very important in maintaining soil fertility and soil ecosystem function, and studies have pointed out that microorganisms are usually sensitive to fertilizer input (Ramirez *et al.*, 2012), and among the different chemical fertilizers, the effects of phosphorus fertilizer on community composition are more pronounced than those of either nitrogen or potassium (Watanabe *et al.*, 2010; Murase *et al.*, 2015; Siddikee *et al.*, 2016). Ji-Chen *et al.* (2018) also proposed that different fertilization methods change the abundance of fungal groups, which were grouped according to their nutritional strategies. Compared with mineral fertilization, soil organic input increased soil fungal α-diversity. Some archaea, especially ammonia-oxidizing archaea (AOA), also respond to fertilization, but less so than ammonia-oxidizing bacteria (AOB), even if the number of AOA is hundreds of times greater (Fan *et al.*, 2011; Qian *et al.*, 2017).

Bacteria and fungi usually account for more than 90% of the total soil microorganisms and are the main regulators of soil organic matter decomposition and nutrient dynamics (Six *et al.*, 2006). Previous studies have shown that the combined application of organic and inorganic fertilizers significantly increases the soil microbial biomass (SMBC) in fluvo-aquic soil, black soil (Wang *et al.*, 2004) and grey desert soil (Yong-Mei *et al.*, 2014). This is closely related to the application of organic and inorganic fertilizers to soil, which not only adds a variety of organic and inorganic nutrients required by soil organisms and crops but also improves the physical and chemical properties of the soil itself. Although the research conclusions on the responses of SMBC to the application of chemical fertilizers are quite different (Cai, 2002; Cao *et al.*, 2006; Zhang *et al.*, 2007), most studies report that long-term high-intensity application of chemical fertilizers is not conducive to the maintenance of soil microbial diversity and easily degrades soil quality (Liu *et al.*, 2008). There are certain differences in the degrees of influence of different fertilization measures and cycles on the structures of soil microbial communities. In addition to soil factors, these differences are also affected by plant types (Vivanco *et al.*, 2018; Li *et al.*, 2019). Because the plant rhizosphere itself is also a unique niche, the structure of microbial community is shaped by releasing specific substrates or specific physical, chemical and biological environment created by the plant root in terms of O_2, pH, etc. (Savka and Farrand, 1997; Singh *et al.*, 2004). The compositions of soil bacterial communities after different inorganic and organic long-term treatments differ, while short-term fertilization treatments only have slight impacts (Bei *et al.*, 2018; Guo *et al.*, 2019). The study of Cui *et al.* (2018) showed that long-term application of NPK fertilizer significantly increased the abundance of Nitrospirae in red rice soil, while manure increased the abundances of Proteobacteria, Chloroflexi and Firmicutes. However, the most abundant Actinobacteria and Planctomycetes were detected in soil treated with a combined application of manure and chemical NPK fertilizer. In addition, the application of organic fertilizer can significantly enrich Firmicutes abundance. In the study of Kai-Le *et al.* (2017), with decreases in soil pH under different fertilization treatments, the ratio of AOA to AOB abundance greatly increased, indicating that the pH of red paddy soil is an important influence on AOA and AOB abundance and community structure. The application of nitrogen, phosphorus, potassium and pig manure fertilizers can increase soil pH, improve soil organic carbon content, increase prokaryotic diversity and improve the community structure of prokaryotic organisms (Kumar *et al.*, 2018; Ye *et al.*, 2019). Duan *et al.* (2018) found that, compared with conventional fertilization, side-deep fertilization slightly increased potential nitrification, significantly reduced denitrification enzyme activity and significantly increased soil NH_4^+-N content. The side-deep fertilization treatment provided the highest AOA terminal restriction fragments (TRFs). There was no significant change in other AOB TRFs with different fertilization treatments. Therefore, it is believed that side-deep fertilization can significantly affect the structure of nitrogen-functional microbial communities.

In summary, side-deep fertilization can change the types and abundance of soil microorganisms, thereby improving soil fertility, maintaining the soil ecosystem and providing a good growth environment for rice. This can be achieved by applying different types and proportions of fertilizers; however, the impacts of side depth fertilization on soil microorganisms are not yet clear and further research is needed.

Concluding remarks

Although some progress has been made in the research on rice side-deep fertilization technology, and the application of related technologies and products has achieved some results, some problems remain. To achieve high-efficiency and high-quality rice production and sustainable agriculture, research on side-deep fertilization should focus on the basic aspects of rice nutrition and high-efficiency diagnostic technology to guide the implementation of side-deep fertilization technology. On the other hand, special high-efficiency fertilizers for side-deep fertilization should be developed and supporting technology should be strengthened. There is a need for research and development of side-deep fertilization devices suitable for the agronomic characteristics of various regions, and of the key components of side-deep fertilization devices. There should be a focus on the impacts of fertilization depth and fertilizer types and quantities on soil microbes and crop yield and growth.

Research and application of accurate, high-efficiency, rice nutrition diagnostic technology

In view of the long growing season of rice, the easy loss of nutrients in the field, and the lack of nutrients and hidden hunger during the growth period, research on precise and efficient diagnosis of rice nutrition should be carried out. There is a need to clarify the molecular responses of rice to nitrogen, phosphorus and potassium abundance and to explore the precise diagnosis of nutrient abundance and deficiency genes. The characteristic bands suitable for diagnosing rice nutrient abundance and deficiency should be screened and qualitative diagnostic models and quantitative predictive models based on rice canopy hyperspectral information and multispectral images should be established. Through field verification, rapid nutrient diagnosis technology for use in the process of rice growth should be developed. Combining drones, medium-resolution multispectral remote-sensing images and crop growth models could be done to predict rice growth and regional nutrient abundance, with a view to providing technical support for the implementation of side-deep fertilization technology.

Development of high-efficiency fertilizers and supporting technology for use in side-deep fertilization

According to the characteristics of side-deep fertilization operations and regional planting characteristics, and through field experiments and test analyses in rice-producing areas, research is needed to clarify the characteristics of soil nutrient supply in different regions and the nutrient demands of different types of rice. Based on the nutrient requirements of high-yield rice and the nutrient pollution control standards of farmland ecosystems, we need to formulate and improve the total control standards of nitrogen, phosphorus and potassium for high-yield and high-quality rice production in different regions. Based on the characteristics of soil nutrients in the main rice-producing areas, nutrient absorption and side-deep fertilization devices, special fertilizers for rice in different regions should be formulated. In order to reduce labor requirements, we must strengthen research and development of full-nutrient slow-release fertilizers for rice that only require one or two applications.

Research has been carried out in different rice-producing areas to clarify the optimal ratios and amounts of organic materials, such as animal manure, straw and green manure, needed to replace chemical fertilizers. There is a need to analyze the synergistic effects and mechanisms of organic and inorganic fertilizers, and to establish fertilizer regimes based on alternative fertilizers such as livestock manure, straw and green manure. Research and development of organic fertilizers suitable for side-deep fertilization technology are needed to determine the best application periods, amounts and methods for chemical fertilizers, organic fertilizers and mixed products.

Optimization of side-deep fertilization equipment according to agronomic characteristics

If side-deep fertilization devices are incompatible with the fertilizer and agronomic characteristics, the uniformity of fertilization will be reduced, and the amount of fertilization required will be difficult to accurately grasp. In addition, it may lead to inconsistencies in the amount of fertilizer applied between rows during field operations. Eventually, this will lead to low fertilizer utilization efficiency and uneven rice growth, which will reduce the yield and quality of rice. The key equipment in rice side-deep fertilization includes the fertilizer discharge device, fertilizer delivery device and sensors. The core is the discharge device, which provides a uniform fertilizer flow and lays the foundation for achieving fertilization that meets the agronomic requirements. The fertilizer conveying device transports the fertilizer from the corrugated pipe to the groove drawn by the opener, which determines the drop point and posture of the fertilizer, and directly influences the fertilization effect. Sensors are an important part of variable side-deep fertilization devices and are also a key device in realizing the development of rice side-deep fertilization devices that are automated and unmanned. However, due to the complex movements and interactions of key components, the fertilization process can be seriously affected by factors such as soil and agronomy. It is still necessary to further study the working mechanisms of fertilizer discharge and conveying devices and to optimize them. The application of remote-sensing technology, machine vision, speed, attitude and other sensors to side-deep fertilization devices should be strengthened, with the development of intelligent control systems and optimization of algorithms to reduce delays so that unmanned and intelligent side-deep fertilization devices will become more practical. It is of great significance to reduce labor intensity, improve operation quality and improve resource utilization efficiency.

Constructing agronomic systems based on side-deep fertilization technology and exploring its influence on rice and soil

There is a need to clarify the different nutrient requirements of different rice varieties in terms of side-deep fertilization. We need to screen rice varieties with high-efficiency nitrogen and phosphorus utilization, tap the biological potential of efficient nutrient utilization, optimize cultivation measures such as seed treatment, density regulation, plant and row spacing, reasonable crop rotation, ditching and ridge cultivation, and construct an agronomic system based on high-efficiency side-deep fertilization technology.

There is a need to study the influences of fertilizer types, quantity, ratio, fertilization depth and working tools on the growth, development, yield and quality of rice plants, and establish a synergistic side-deep fertilization system. It is also important to clarify the impacts of side-deep fertilization on soil and soil microorganisms, and to study how side-deep fertilization can enrich microbial communities. Moreover, current soil acidification is serious and residual toxic and harmful substances in the soil are increasing. Strengthening research on side-deep fertilization methods that improve the soil and reduce harmful substances is also important.

Acknowledgements. This work is supported by the China's National Key R & D Plan-Research and demonstration on combination of agricultural machinery and agronomy of rice unmanned production model (2021YFD200060502); China's National Key R & D Plan-Study and Demonstration on High Efficiency Utilization of Fertilizer and Straw Mulching Technology of Japonica Rice in Semi Humid Region (2018YFD0300105); China's National Key R & D Plan-Fertilizer Cultivation and High Yield and Efficiency Cultivation Model of Paddy Field in North (2016YFD0300909).

References

Alchanatis V, Ridel L, Hetzroni A and Yaroslavsky L (2005) Weed detection in multi-spectral images of cotton fields. *Computers and Electronics in Agriculture* **47**, 243–260.

Alimate B, Fofana B, Sansan Y, Ebenezer S, Robert A and Opoku A (2015) Effect of deep placement with urea super granule on nitrogen use efficiency of irrigated rice in Sourou Valley (Burkina Faso). *Nutrient Cycling in Agroecosystems* **102**, 79–89.

Anh PTQ, Gomi T, MacDonald LH, Mizugaki S, Van Khoa P and Furuichi T (2014) Linkages among land use, macronutrient levels, and soil erosion in northern Vietnam: a plot-scale study. *Geoderma* **23**, 352–362.

Anton F, Hubert Z and Georg B (2007) Mass Flowmeter for Screw Conveyors Based on Capacitive Sensing. *Instrumentation & Measurement Technology Conference*. IEEE, Warsaw, Poland. https://doi.org/10.1109/IMTC.2007.379169.

Aphale A, Bolander N, Park J, Shaw L, Svec J and Wassgren C (2003) Granular fertilizer particle dynamics on and off a spinner spreader. *Biosystems Engineering* **85**, 319–329.

Arif BT (2010) Variable rate fertilizer application in Turkish wheat agriculture: economic assessment. *African Journal of Agricultural Research* **5**, 647–652.

Atique-ur R, Farooq M, Nawaz A and Ahmad R (2014) Influence of boron nutrition on the rice productivity, kernel quality and biofortification in different production systems. *Field Crops Research* **169**, 123–131.

Azeem B, Kushaari KZ, Man ZB, Basit A and Trinh TH (2014) Review on materials & methods to produce controlled release coated urea fertilizer. *Journal of Controlled Release* **181**, 11–21.

Bacenetti J, Paleari L, Tartarini S, Vesely FM, Foi M, Movedi E, Ravasi RA, Durello S, Ceravolo C, Amicizia F and Confalonieri R (2020) May smart technologies reduce the environmental impact of nitrogen fertilization? A case study for paddy rice. *Science of the Total Environment* **715**, 136956.

Behera SK and Panda RK (2013) Effect of fertilization on crop responses and solute transport for rice crop in a sub-humid and sub-tropical region. *Paddy & Water Environment* **11**, 227–239.

Bei SK, Zhang YL, Li TT, Christie P, Li XL and Zhang JL (2018) Response of the soil microbial community to different fertilizer inputs in a wheat-maize rotation on a calcareous soil. *Agriculture Ecosystems & Environment* **260**, 58–69.

Birrell SJ and Hummel JW (2001) Real-time multi ISFET/FIA soil analysis system with automatic sample extraction. *Computers and Electronics in Agriculture* **32**, 45–67.

Burks TF, Shearer SA, Heath JR and Donohue KD (2005) Evaluation of neural-network classifiers for weed species discrimination. *Biosystems Engineering* **91**, 293–304.

Cai XB (2002) Effect of different methods of application on degenerated soil in middle part of Tibet. *Journal of Soil Water Conservation* **16**, 51–76.

Camacho-Tamayo JH, Barbosa AM, Pérez NM, Leiva FR and Rodríguez GA (2009) Operational characteristics of four metering systems for agricultural fertilizers and amendments. *Engenharia Agrícola* **29**, 605–613.

Cao ZP, Hu C, Ye ZN and Wu WL (2006) Impact of soil fertility maintaining practice on microbial biomass carbon in high production agro-ecosystem in northern China. *Acta Ecologica Sinica* **26**, 1486–1493.

Cao SJ, Wang SJ, Wang Y, Feng GZ, Yan L, Yuan YM, Du S and Gao Q (2019) Physical properties and suitability of common base fertilizers for blending fertilizers. *Journal of Plant Nutrition and Fertilizers* **25**, 647–653.

Champagne ET, Bett-Garber KL, Grimm CC and McClung AM (2007) Effects of organic fertility management on physicochemical properties and sensory quality of diverse rice cultivars. *Cereal Chemistry* **84**, 320–327.

Chen XF, Luo XW, Wang ZM, Zhang MH, Hu L, Yang WW, Zeng S, Zang Y, Wei HD and Zheng L (2015) Design and experiment of fertilizer distribution apparatus with double-level screws. *Transactions of the Chinese Society of Agricultural Engineering* **31**, 10–16.

Chen HZ, Zhu DF, Lin XQ and Zhang YP (2010) Effect of microbial fertilizer on yield and nitrogen use efficiency in rice. *Journal of Nuclear Agricultural Sciences* **24**, 1051–1055.

Cool S, Pieters J, Mertens KC, Hijazi B and Vangeyte J (2014) A simulation of the influence of spinning on the ballistic flight of spherical fertiliser grains. *Computers and Electronics in Agriculture* **105**, 121–131.

Corbin JL, Orlowski JM, Harrell DL, Golden BR, Larry F and Jason KL (2016) Nitrogen strategy and seeding rate affect rice lodging, yield, and economic returns in the midsouthern United States. *Agronomy Journal* **108**, 1938–1943.

Crusciol CAC, Costa AD, Borghi E, Castro GSA and Fernandes DM (2010) Fertilizer distribution mechanisms and side dress nitrogen fertilization in upland rice under no-tillage system. *Scientia Agricola* **67**, 562–569.

Cui ZL, Zhang FS, Chen XP, Miao YX, Li JL, Shi LW, Xu JF, Ye YL, Liu CS, Yang ZP, Zhang Q, Huang SM and Bao DJ (2008) On-farm evaluation of an in-season nitrogen management strategy based on soil Nmin test. *Field Crops Research* **105**, 48–55.

Cui BS, Zhao H, Li X, Zhang KJ, Ren HL and Bai J (2010) Temporal and spatial distributions of soil nutrients in Hani terraced paddy fields, Southwestern China. *Procedia Environmental Sciences* **2**, 1032–1042.

Cui XW, Zhang YZ, Gao JS, Peng FY and Gao P (2018) Long-term combined application of manure and chemical fertilizer sustained higher nutrient status and rhizospheric bacterial diversity in reddish paddy soil of central south China. *Scientific reports* **8**, 55–64.

Ding YF, Zhao CH and Wang QS (2003) Effect of application stage of panicle fertilizer on rice grain yield and the utilization of nitrogen. *Journal of Nanjing Agricultural University* **26**, 5–8.

Drescher GL, Silva LSD, Sarfaraz Q, Drescher MS, Brunetto G, Silva AAKD, Tassinari A and Silva L (2021) Rice nitrogen uptake as affected by different nitrogen application depths. *Archives of Agronomy and Soil Science* **67**, 53–65.

Du J, Yang QJ, Xia JF and Li G (2020) Discrete element modeling and verification of an outer groove wheel fertilizer applicator with helical teeth. *Transactions of the ASABE* **63**, 659–664.

Duan R, Long XE, Tang YF, Wen J, Su SM, Bai LY, Liu RL and Zeng XB (2018) Effects of different fertilizer application methods on the community of nitrifiers and denitrifiers in a paddy soil. *Journal of Soil & Sediments* **18**, 24–38.

Falkowski PG, Fenchel T and Delong EF (2008) The microbial engines that drive Earth's biogeochemical cycles. *Science* **320**, 1034–1039.

Fan FL, Yang QB, Li ZZ, Wei D, Cui XA and Liang YC (2011) Impacts of organic and inorganic fertilizers on nitrification in a cold climate soil are linked to the bacterial ammonia oxidizer community. *Microbial Ecology* **62**, 982–990.

Fu WQ, Meng ZJ, Huang WQ, Chen LP and Wang X (2008) Variable rate fertilizer control system based on CAN bus. *Transactions of the Chinese Society of Agricultural Engineering* **24**, 127–132.

Grift TE, Walker JT and Hofstee JW (1997) Aerodynamic properties of individual fertilizer particles. *Transaction of the ASAE* **40**, 13–20.

Guo Z, Han JC, Li J, Xu Y, Wang XL and Li Y (2019) Effects of long-term fertilization on soil organic carbon mineralization and microbial community structure. *PLoS ONE* **14**, 216–227.

Hofstee JW and Huisman W (1990) Handling and spreading of fertilizers part 1: physical properties of fertilizer in relation to particle motion. *Journal of Agricultural Engineering Research* **47**, 213–234.

Hu KJ (2013) *The Research on Venturi Feeder in Pneumatic Conveying System* (M.S. thesis). Qingdao University of Science and Technology, Qingdao, China.

Huang H (2021) *Effect of Different Lateral and Deep Nitrogen Application Methods on Nitrogen Utilization, Grain Yield, and Quality of Rice* (M.S. thesis). Yangzhou University, Yangzhou, China.

Huang H, Jiang HX, Liu GM, Yuan JQ, Wang Y, Zhao C, Wang WL, Huo ZY, Xu K, Dai QG, Zhang HC, Li DJ and Liu GL (2021) Effects of side deep placement of nitrogen on rice yield and nitrogen use efficiency. *Acta Agronomica Sinica* **47**, 232–2249.

Huda A, Gaihre YK, Islam MR, Singh U, Islam MR, Sanabria J, Satter MA, Afroz H, Halder A and Jahiruddin M (2016) Floodwater ammonium, nitrogen use efficiency and rice yields with fertilizer deep placement and alternate wetting and drying under triple rice cropping systems. *Nutrient Cycling in Agroecosystems* **104**, 53–66.

Ishfaq M, Akbar N, Zulfiqar U, Jabran K and Farooq M (2021) Influence of nitrogen fertilization pattern on productivity, nitrogen use efficiencies, and profitability in different rice production systems. *Journal of Soil Science and Plant Nutrition* **21**, 312–324. https://doi.org/10.1007/s42729-020-00349-0.

Ji HJ, Zhang XX, Dai ZY, Wang BH, Tan CL, Zhang HX and Zhao BH (2011) Effect of fertilizer management on grain quality of direct-seeding japonica rice Yang jing 4038. *Journal of Yangzhou University (Agricultural and Life Science Edition)* **32**, 39–44.

Jiang DL, Chen XG, Yan LM, Mo YS and Yang SM (2019) Design and experiment on spiral impurity cleaning device for profile modeling residual plastic film collector. *Transactions of the Chinese Society for Agricultural Machinery* **50**, 137–145.

Ji-Chen W, Geoff R, Qi-Wei H and Qi-Rong S (2018) Plant growth stages and fertilization regimes drive soil fungal community compositions in a wheat-rice rotation system. *Biology & Fertility of Soils* **54**, 731–742.

Jin-Feng W, Guan-Bao G, Wu-Xiong W, Jin-Wu W, Dong-Wei Y and Bo-Wen C (2018) Design and experiment of key components of side deep fertilization device for paddy field. *Transactions of the Chinese Society for Agricultural Machinery* **49**, 92–104.

Jin-Feng W, Wen-Hu S, Wu-Xiong W, Jin-Wu W, Qi W and Xin-Sheng C (2021) Design and experiment of disc ejection type paddy field side deep fertilization device. *Transactions of the Chinese Society for Agricultural Machinery* **52**, 62–72.

Jing J, Zhang F, Rengel Z and Shen J (2013) Localized fertilization with P plus N elicits ammonium-dependent enhancement of maize root growth and nutrient uptake. *Field Crops Research* **133**, 176–185.

Kai-Le Z, Lin C, Yong L, Philip-C B, JianMing X and Yu L (2017) The effects of combinations of biochar, lime, and organic fertilizer on nitrification and nitrifiers. *Biology & Fertility of Soils* **53**, 77–87.

Kargbo MB, Pan SG and Mo ZW (2016) Physiological basis of improved performance of super rice (*Oryza sativa* L.) to deep placed fertilizer with precision hill-drilling machine. *International Journal of Agriculture and Biology* **18**, 797–804.

Ke X, Jun Z, Hong-Cheng Z, Jin H, Bao-Wei G, Zhong-Yang H, Qi-Gen D, Hai-Yan W, Hui G, Pei-Jian Z, Fei-Hu C, Da-Shan H, Zhong-Ping C and Guo-Liang C (2014) Nitrogen managements of late japonica rice in double-cropping rice area. *Journal of Plant Nutrition and Fertilizer* **20**, 1063–1075.

Khanal S, Anex RP, Gelder BK and Wolter C (2014) Nitrogen balance in Iowa and the implications of corn-stover harvesting. *Agriculture Ecosystems & Environment* **183**, 21–30.

Kim YJ, Kim HJ, Ryu KH and Rhee JY (2008) Fertiliser application performance of a variable-rate pneumatic granular applicator for rice production. *Biosystems Engineering* **100**, 498–510.

Kodaira M and Shibusawa S (2013) Using a mobile real-time soil visible-near infrared sensor for high resolution soil property mapping. *Geoderma* **199**, 64–79.

Kretz D, Callau-Monje S, Hitschler M, Hien A and Raedle M (2015) Discrete element method (DEM) simulation and validation of a screw feeder system. *Powder Technology* **287**, 131–138.

Kumar VJF and Durairaj CD (2000) Influence of head geometry on the distributive performance of air-assisted seed drills. *Journal of Agricultural Engineering Research* **75**, 81–95.

Kumar U, Nayak AK, Shahid M, Gupta VVSR, Panneerselvam P, Mohanty S, Kaviraj M, Kumar A, Chatterjee D, Lal B, Gautam P, Tripathi R and Panda BB (2018) Continuous application of inorganic and organic fertilizers over 47 years in paddy soil alters the bacterial community structure and its influence on rice production. *Agriculture, Ecosystems & Environment* **262**, 65–75.

Leng XL, Li ML, Zhang LZ and Ren WJ (2018) Design and experiment of horizontal pneumatic screw combination adjustable quantitative fertilizer feeding device for granular fertilizer. *Transactions of the Chinese Society of Agricultural Engineering* **34**, 9–18.

Li J, Webb C, Pandiella SS, Campbell GM and Dyakowski T (2005) Solids deposition in low-velocity slug flow pneumatic conveying. *Chemical Engineering & Processing* **44**, 167–173.

https://doi.org/10.1017/S1742170522000151 Published online by Cambridge University Press

Li HB, Zhang FS and Shen JB (2012) Contribution of root proliferation in nutrient-rich patches to nutrient uptake and growth of maize. *Pedosphere* **22**, 776–784.
Li M, Wang T and Li L (2019) Effects of long-term nitrogen fertilizer application on rhizosphere microorganisms under different soil types. *Polish Journal of Environmental Studies* **28**, 1771–1784.
Lin ZC, Dai QG and Ye SC (2012) Effects of nitrogen application levels on ammonia volatilization and nitrogen utilization during rice growing season. *Rice Science* **19**, 125–134.
Lin DX, Fan XH and Hu F (2017) Ammonia volatilization and nitrogen utilization efficiency in response to urea application in rice fields of the Taihu lake region, China. *Pedosphere* **17**, 639–645.
Ling QH (2007) *The Theory and Technology of Precise and Quantitative Cultivation of Rice*, 1st Edn. Beijing: Agriculture Press.
Linquist BA, Adviento-Borbe MA, Pittelkow CM, Van Kessel C and Van Groenigen KJ (2012) Fertilizer management practices and greenhouse gas emissions from rice systems: a quantitative review and analysis. *Field Crops Research* **135**, 10–21.
Liu H, Lin YH, Zhang YS, Tan XX and Wang XH (2008) Effects of long-term fertilization on biodiversity and enzyme activity in grey desert soil. *Acta Ecologica Sinica* **28**, 3898–3904.
Liu RL, Li YH, Wang F, Zhao TC, Chen C, Hong Y and Zhou LN (2014) Effect of slow-release fertilizer side bar fertilization technology on rice yield and nitrogen use efficiency. *Journal of Agricultural Resources and Environment* **31**, 45–49.
Liu TQ, Fan DJ, Zhang XX, Chen J, Li CF and Cao CG (2015) Deep placement of nitrogen fertilizers reduces ammonia volatilization and increases nitrogen utilization efficiency in no-tillage paddy fields in central China. *Field Crops Research* **184**, 80–90.
Li-Wei L, Zhi-Jun M, Xiao-Ou W, Xiao-Fei A, Pei W and Guang-Wei W (2018) Simulation analysis of gas-solid two phase flow in pneumatic conveying fertilizer feeder of rice fertilizer applicator. *Transactions of the Chinese Society for Agricultural Machinery* **49**, 171–180.
Lyu YF, Yang XD, Pan HY, Zhang XH, Cao HX, Ulgiati S, Wu J, Zhang YZ, Wang GY and Xiao YL (2021) Impact of fertilization schemes with different ratios of urea to controlled release nitrogen fertilizer on environmental sustainability, nitrogen use efficiency and economic benefit of rice production: a study case from southwest China. *Journal of Cleaner Production* **293**, 116–128.
Maona L, Yun-Ling W, Ardeshir A and Hai-Jun Y (2018) Effects of application methods and urea rates on ammonia volatilization, yields and fine root biomass of alfalfa. *Field Crops Research* **218**, 115–125.
Marcello B, Pietro G and Paolo M (2013) Aerodynamic properties of six organo-mineral fertiliser particles. *Journal of Agricultural Engineering* **2**, 83–95. https://doi.org/10.4081/jae.2013.s2.e83.
Massoudi M (2001) On the flow of granular materials with variable material properties. *International Journal of Non-Linear Mechanics* **36**, 25–37.
Min Z, Yuan-Lin Y, Miao Z, Bo-Wen Z, Yu-Hua T, Bin Y and Zhao-Liang Z (2017) Integration of urea deep placement and organic addition for improving yield and soil properties and decreasing N loss in paddy field. *Agriculture Ecosystems & Environment* **247**, 236–245.
Murase J, Hida A, Ogawa K, Nonoyama T, Yoshikawa N and Imai K (2015) Impact of long-term fertilizer treatment on the microeukaryotic community structure of a rice field soil. *Soil Biology & Biochemistry* **80**, 237–243.
Pan GK, Zhou P, Li ZP, Smith P, Li LQ, Qiu DS, Zhang XH, Xu XB, Shen SY and Chen XM (2009) Combined inorganic/organic fertilization enhances N efficiency and increases rice productivity through organic carbon accumulation in a rice paddy from the Tai Lake Region, China. *Agriculture Ecosystems & Environment* **131**, 274–280.
Pan SQ, Zhao YX, Jin L, Qu GB and Tian Y (2016) Design and experimental research of external grooved wheel fertilizer apparatus of 2BFJ-6 type variable rate fertilizer applicator. *Journal of Chinese Agricultural Mechanization* **37**, 40–42.
Parkash YS, Bhadoria PBS, Amitava R and Rakshit A (2002) Relative efficacy of organic manure in improving milling and cooking quality of rice. *International Rice Research Notes* **27**, 43–44.
Patterson DE and Reece AR (1962) The theory of the centrifugal distributor. I: Motion on the disc, near-centre feed. *Journal of Agricultural Engineering Research* **7**, 232–240.
Pennock D, Bedard-Haughn A, Kiss J and Van DKG (2014) Application of hydropedology to predictive mapping of wetland soils in the Canadian prairie pothole region. *Geoderma* **23**, 199–211.
Qi XL, Nie LX, Liu HY, Peng SB, Shah F, Huang JL, Cui KH and Sun LM (2012) Grain yield and apparent N recovery efficiency of dry direct-seeded rice under different N treatments aimed to reduce soil ammonia volatilization. *Field Crops Research* **134**, 138–143.
Qian Z, Guo-Qing L, David-D M and Wei Z (2017) Variable responses of ammonia oxidizers across soil particle-size fractions affect nitrification in a long-term fertilizer experiment. *Soil Biology and Biochemistry* **105**, 25–36.
Qin J, Yang ZY, Sun YJ, Xu H, Lv TF, Dai Z, Zheng JK, Jiang KF and Ma J (2017) Effects of nitrogen topdressing for panicle initiation on leaf morphology, photosynthetic production and grain yield of two middle-season hybrid rice. *Chinese Journal of Rice Science* **31**, 391–399.
Rahman MH, Haque K and Khan M (2021) A review on application of controlled released fertilizers influencing the sustainable agricultural production: a cleaner production process. *Environmental Technology & Innovation* **23**, 101697.
Ramirez KS, Craine JM and Fierer N (2012) Consistent effects of nitrogen amendments on soil microbial communities and processes across biomes. *Global Change Biology* **18**, 1918–1927.
Roberts TL, Norman RJ, Ross WJ, Slato NA and Wilson CE (2012) Soil depth coupled with soil nitrogen and carbon can improve fertilization of rice in Arkansas. *Soil Science Society of America Journal* **76**, 268.
Rudolph S, Wongleecharoen C, Lark RM, Marchant BP, Garre S, Herbst M and Weihermiiller L (2016) Soil apparent conductivity measurements for planning and analysis of agricultural experiments: a case study from western-Thailand. *Geoderma* **267**, 220–229.
Rychel K, Meurer KHE, Brjesson G, Strmgren M and Ktterer T (2020) Deep N fertilizer placement mitigated N_2O emissions in a Swedish field trial with cereals. *Nutrient Cycling in Agroecosystems* **118**, 42–61. https://doi.org/10.1007/s10705-020-10089-3.
Savant NK and Stangel PJ (1990) Deep placement of urea supergranules in transplanted rice: principles and practices. *Fertilizer Research* **25**, 1–83.
Savin MC, Daigh ALM, Brye KR, Norman R and Miller D (2021) Vertical distribution of fertilizer nitrogen from surface water flooding of a silt loam and clay soil used for rice production. *Soil Use Manage* **37**, 1–8.
Savka MA and Farrand SK (1997) Modification of rhizobacterial populations by engineering bacterium utilization of a novel plantproduced resource. *Nature Biotechnology* **15**, 363–368.
Shi YY, Chen M, Wang XC, Morice OO, Li CG and Ding WM (2018) Design and experiment of variable-rate fertilizer spreader with centrifugal distribution cover for rice paddy surface fertilization. *Transactions of the Chinese Society for Agricultural Machinery* **49**, 86–93.
Siddikee MA, Zereen MI, Li CF and Dai CC (2016) Endophytic fungus *Phomopsis liquidambari* and different doses of N-fertilizer alter microbial community structure and function in rhizosphere of rice. *Scientific Reports* **6**, 32270.
Simon RC, Jan GP, Joris VA, Jan VDB, Koen CM, David REN, Tim CVDG and Jürgen V (2016) Determining the effect of wind on the ballistic flight of fertiliser particles. *Biosystems Engineering* **151**, 425–434.
Singh RA, Singh OP and Singh M (1976) Effect of soil compaction and nitrogen placement on weed population, yield and moisture use pattern of rainfed wheat. *Plant and Soil* **44**, 87–96.
Singh BK, Millard P, Whiteley AS and Murrel JC (2004) Unravelling rhizosphere microbial interactions: opportunities and limitations. *Trends in Microbiology* **12**, 386–393.
Six J, Frey SD, Thiet RK and Batten KM (2006) Bacterial and fungal contributions to carbon sequestration in agroecosystems. *Soil Science Society of America Journal* **70**, 555–569.
Sudduth KA, Drummond ST and Kitchen NR (2001) Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture. *Computers and Electronics in Agriculture* **31**, 239–264.
Sugirbay AM, Zhao J, Nukeshev SO and Chen J (2020) Determination of pin-roller parameters and evaluation of the uniformity of granular fertilizer application metering devices in precision farming. *Computers and Electronics in Agriculture* **179**, 10–35.

Sun YJ, Sun YY, Xu H, Yang ZY, Qing J, Peng Y and Ma J (2013) Effects of water-nitrogen management patterns and combined application of phosphorus and potassium fertilizers on nutrient absorption of hybrid rice Gangyou725. *Scientia Agricultura Sinica* **46**, 1335–1346.

Sun JF, Chen HM, Duan JL, Liu Z and Zhu QC (2020) Mechanical properties of the grooved-wheel drilling particles under multivariate interaction influenced based on 3D printing and EDEM simulation. *Computers and Electronics in Agriculture* **172**, 105–329.

Tian GM, Cai ZC, Cao JL and Li XP (2001) Ammonia volatilization from paddy field and its affecting factors in ZhenJiang hilly region. *Acta Pedologica Sinica* **38**, 324–332.

Tripathi NM, Santo N, Kalman H and Levy A (2018) Experimental analysis of particle velocity and acceleration in vertical dilute phase pneumatic conveying. *Powder Technology* **330**, 239–251.

Vibhu K, Singh U, Patil SK, Magre H, Shrivastava LK, Mishra VN, Das RO, Samadhiya VK, Sanabria J and Diamond R (2008) Rice growth, grain yield, and floodwater nutrient dynamics as affected by nutrient placement method and rate. *Agronomy Journal* **100**, 526–536.

Villette S, Cointault F, Piron E and Chopinet B (2005) Centrifugal spreading: an analytical model for the motion of fertiliser particles on a spinning disc. *Biosystems Engineering* **92**, 157–164.

Vivanco L, Rascovan N and Austin AT (2018) Plant, fungal, bacterial, and nitrogen interactions in the litter layer of a native Patagonian forest. *Peer Journal* **6**, 47–54.

Walker JT, Grift TE and Hofstee JW (1997) Determining effects of fertilizer particle shape on aerodynamic properties. *Transaction of the ASAE* **40**, 21–27.

Wang XB, Wu P, Hu B and Chen QS (2002) Effects of nitrate on the growth of lateral root and nitrogen absorption in rice. *Acta Botanica Sinica* **44**, 678–683.

Wang J, Xie HT, Zhang XD, Zhu P and Wang LL (2004) Effect of fertilization on soil microbial biologic carbon in black soil. *Chinese Journal of Eco-Agriculture* **12**, 118–120.

Wang SS, Mao JR and Liu GW (2005) Mechanism of discharge pulsation of particles feeder and new method of restraining pulsation. *Journal of Xian Jiaotong University* **39**, 39–42.

Wang X, Tang HL and Shen JB (2013) Root responses of maize to spatial heterogenous nitrogen and phosphorus. *Journal of Plant Nutrition & Fertilizer* **19**, 1058–1064.

Wang Y, Williams YK, Illiams K and Jones M (2017) CFD simulation methodology for gas-solid flow in bypass pneumatic conveying-a review. *Applied Thermal Engineering* **125**, 185–208.

Wang XD, Xiang J, Zhang YP, Zhang YK, Wang YL and Chen HZ (2020) Research advances and application of rice mechanized transplanting with side deep fertilization technology. *China Rice* **26**, 53–57.

Watanabe T, Wang G, Taki K, Ohashi Y, Kimura M and Asakawa S (2010) Vertical changes in bacterial and archaeal communities with soil depth in Japanese paddy fields. *Soil Science and Plant Nutrition* **56**, 705–715.

Wei HY, Chen ZF, Xing ZP, Zhou L, Liu QY, Zhang ZZ, Jiang Y, Hu YJ, Zhu JY, Cui PY, Dai QG and Zhang HC (2018) Effects of slow or controlled release fertilizer types and fertilization modes on yield and quality of rice. *Journal of Integrative Agriculture* **17**, 2222–2234.

Wei GJ, Qi B, Jiao W, Shi WS and Jian SC (2020) Design and experiment of mechanical forced fertilizing device for paddy field. *Transactions of the Chinese Society for Agricultural Machinery* **51**, 161–171.

Wen XY, Jia HL, Zhang SW, Yuan HF, Wang G and Chen TY (2020) Test of suspension velocity of granular fertilizer based on EDEM-Fluent coupling. *Transactions of the Chinese Society for Agricultural Machinery* **051**, 69–77.

Wopereis-Pura MM, Watanabe H, Moreira J and Wopereis MCS (2005) Effect of late nitrogen application on rice yield, grain quality and profitability in the Senegal River valley. *European Journal of Agronomy* **17**, 191–198.

Wu JQ and Song XG (2021) Review on development of simultaneous localization and mapping technology. *Journal of Shandong University* **51**, 16–31.

Wu M, Li GL, Li WT, Liu M, Jiang CY and Li ZP (2017) Nitrogen fertilizer deep placement for increased grain yield and nitrogen recovery efficiency in rice grown in subtropical China. *Frontiers in Plant Science* **8**, 12–27.

Wu L, Fei D, Hui H, Min Z, Shuang L, Shi-Lin P and Wan-Jun R (2018) Effect of controlled-release nitrogen fertilizer on grain quality of machine-transplanted hybrid rice. *Journal of Nuclear Agricultural Sciences* **32**, 779–787.

Wu Q, Wang YH, Ding YF, Tao WK, Gao S, Li QX, Li WW, Liu ZH and Li GH (2021) Effects of different types of slow-and controlled-release fertilizers on rice yield. *Journal of Integrative Agriculture* **20**, 1503–1514.

Xiao-Dan W, Ya-Liang W, Yu-Ping Z, Jing X, Yi-Kai Z, De-Feng Z and Hui-Zhe C (2021) The nitrogen topdressing mode of indica-japonica and indica hybrid rice are different after side-deep fertilization with machine transplanting. *Scientific Reports* **11**, 94–105.

Xie XB, Shan SL, Wang YM, Cao FB, Chen JN, Huang M and Zou YB (2019) Dense planting with reducing nitrogen rate increased grain yield and nitrogen use efficiency in two hybrid rice varieties across two light conditions. *Field Crops Research* **236**, 24–32.

Xu JG, Heeraman DA and Wang Y (1993) Fertilizer and temperature effects on urea hydrolysis in undisturbed soil. *Biology & Fertility of Soils* **16**, 63–65.

Yamuangmorn S, Insinjoy R, Lordkaew S, Dell B and Prom-u-thai C (2020) Responses of grain yield and nutrient content to combined zinc and nitrogen fertilizer in upland and wetland rice varieties grown in waterlogged and well-drained condition. *Journal of Soil Science and Plant Nutrition* **20**, 2112–2122.

Yang MJ, Yang L and Li QD (2003) Agricultural mechanization system of rice production of Japan and proposal for China. *Transactions of the Chinese Society of Agricultural Engineering* **19**, 77–82.

Yang JC, Du Y, Wu CF, Liu LJ, Wang ZQ and Zhu QS (2006) Growth and development characteristics of super-high-yielding mid-season japonica rice. *Scientia Agricultura Sinica* **39**, 1336–1345.

Yang YD, Ren YF, Wang XQ, Hu YG, Wang ZM and Zeng ZH (2018) Ammonia-oxidizing archaea and bacteria responding differently to fertilizer type and irrigation frequency as revealed by Illumina Miseq sequencing. *Journal of Soils & Sediments* **18**, 1029–1040.

Yang QL, Li ZH, Li HW, He J, Wang QJ and Lu CY (2019) Numerical analysis of particle motion in pneumatic centralized fertilizer distribution device based on CFD-DEM. *Transactions of the Chinese Society for Agricultural Machinery* **50**, 81–89.

Yang WW, Fang LY, Luo XW, Li H and Ye YQ (2020) Experimental study of the effects of discharge port parameters on the fertilizing performance for fertilizer distribution apparatus with screw. *Transactions of the Chinese Society of Agricultural Engineering* **36**, 8–20.

Yao ZS, Zheng XH, Zhang YN, Liu CY, Wang R, Lin S, Zuo Q and Butterbach-Bahl K (2017) Urea deep placement reduces yield-scaled greenhouse gas (CH_4 and N_2O) and NO emissions from a ground cover rice production system. *Scientific Reports* **7**, 114–125.

Yao YL, Zhang M, Tian YH, Zhao M, Zhang BW, Zeng K, Zhao M and Yin B (2018a) Urea deep placement in combination with Azolla for reducing nitrogen loss and improving fertilizer nitrogen recovery in rice field. *Field Crops Research* **218**, 141–149.

Yao YL, Zhang M and Tian YH (2018b) Urea deep placement for minimizing NH_3 loss in an intensive rice cropping system. *Field Crops Research* **218**, 254–266.

Yao-Ming L, Li-Zhang X, Zhong-Ping X and Ling-Li D (2005) Research advances of rice planting mechanization in Japan. *Transactions of the Chinese Society of Agricultural Engineering* **21**, 181–184.

Yatskui A, Lemiere JP and Cointaulf F (2017) Influence of the divider head functioning conditions and geometry on the seed's distribution accuracy of the air-seeder. *Biosystems Engineering* **161**, 120–134.

Ye GP, Lin YX, Liu DY, Chen ZM, Bolan N, Fan JB and Ding WX (2019) Long-term application of manure over plant residues mitigates acidification, builds soil organic carbon and shifts prokaryotic diversity in acidic ultisols. *Applied Soil Ecology* **133**, 24–33.

Yi Q, Feng YW, Yang SM, Lu YS, Fu HT, Li P, Jiang RP and Tang SH (2013) Methane and nitrous oxide emissions in paddy field as influenced by fertilization. *Ecology and Environmental Sciences* **22**, 1432–1437.

Yong-Mei X, Jin-Yu Y, Guang-Hui Z, Jiu-Sheng S, Hua L and Xi-He W (2014) The relationship between long-term carbon input and microbial quotient in grey desert soil of cropland. *Xinjiang Agricultural Sciences* **51**, 2338–2346.

Yu WX, Hu XC, Wang XX, Chen YL, Dong ZZ and Wu LH (2016) Effects of slow controlled-release fertilizers on yield, quality and economic benefits of Indica-japonica hybrid rice. *Chinese Agricultural Science Bulletin* **32**, 1–5.

Yuan J, Li M, Ye F and Zhou Z (2020) Dynamic characteristic analysis of vertical screw conveyor in variable screw section condition. *Science Progress* **103**, 321–333.

Zhang M, Bai Z, Zhang W, Ding XL, Song DY, Zhu JF and Zhu P (2007) Seasonal change of the long-term fertilization on microbial C and N of arable mollisol. *Ecology and Environment* **16**, 1498–1503.

Zhang HC, Wu GC, Dai QG, Huo ZY, Xu K, Gao H, Wei HY, Duanmu YX, Sun JY, Zhao PH, Sha AQ, Zhou YY, Li DJ, Xiao YC, Wang BJ and Wu AG (2010) Formulation of and cultural approach to super-high yielding in japonica hybrid rice. *Hybrid Rice* **25**, 346–353.

Zhang XD, Guo DW, Blennow A and Zorb C (2021) Mineral nutrients and crop starch quality. *Trends in Food Science & Technology* **114**, 45–54.

Zhao CJ, Xun XZ, Wang X, Chen LP, Pan YC and Meng ZJ (2003) Advance and prospects of precision agriculture technology system. *Transactions of the Chinese Society of Agricultural Engineering* **19**, 712.

Zhao YH, Xiong X and Wu CX (2021) Effects of deep placement of fertilizer on periphytic biofilm development and nitrogen cycling in paddy systems. *Pedosphere* **31**, 125–133.

Zhu CH, Chen HZ, Zhang YP, Xiang J, Zhang YK, Yi ZH and Zhu DF (2019a) Effects of side deep mechanical fertilization on yield and nitrogen use efficiency of early rice. *China Rice* **25**, 40–43.

Zhu CH, Xiang J, Zhang YP, Zhang YK, Zhu DF and Chen HZ (2019b) Mechanized transplanting with side deep fertilization increases yield and nitrogen use efficiency of rice in eastern China. *Scientific Reports* **9**, 56–67.

Zhu CH, Zhang YP, Xiang J, Zhang YK, Wu H, Wang YL, Zhu DF and Chen HZ (2019c) Effects of side deep fertilization on yield formation and nitrogen utilization of mechanized transplanting rice. *Scientia Agricultura Sinica* **52**, 4228–4239.

Zhu CH, Li XY, Chen HZ, Wu H, Ouyang YY, Yu JQ, Huang BM and Luo X (2020) Effects of side deep placement of nitrogen fertilizer on yield and nitrogen utilization efficiency of mechanized direct-seeded rice. *Journal of Nuclear Agricultural Sciences* **34**, 2051–2058.

Zuo XJ (2016) *Design and Experiment on Air-Blast Rice Side Deep Precision Fertilization Device* (M.S. thesis). Northwest A & F University, Yangling, China.

Zuo XJ, Wu GW, Fu WQ, Li LW, Wei XL and Zhao CJ (2016) Design and experiment on air-blast rice side deep precision fertilization device. *Transactions of the Chinese Society of Agricultural Engineering* **32**, 14–21.