RESEARCH PROGRESS ON MECHANICAL-TYPE AND PNEUMATIC-TYPE PRECISION SEED METERING DEVICES: A REVIEW
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机械式与气力式精量排种器研究进展综述

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ABSTRACT
The seed metering device was identified as the core actuating component of precision seeding equipment, directly determining seeding accuracy, seed spacing uniformity, seedling emergence rate, and crop yield. This review systematically examined the technological evolution and research status of mechanical-type and pneumatic-type precision seed metering devices. The identified limitations of mechanical-type devices included low seed filling efficiency, poor seed clearing performance, insufficient operational stability at high speeds, and significant interference from field vibrations. Pneumatic-type devices were found to face technical bottlenecks including difficulties in precision seeding of small-sized seeds, high air pressure loss, poor airtightness, and susceptibility to hole clogging. Recent advances in structural innovation, mechanism analysis, parameter optimization, and performance improvement were summarized. A comparative analysis was conducted on the technical advantages and applicable scenarios of the two mainstream seed metering device types. Future development trends were envisioned towards high-speed and high-efficiency operation, universal adaptability, intelligent monitoring, and low-damage energy saving, providing a reference for the optimal design and technological upgrade of precision seeding equipment.

摘要
排种器是精量播种装备的核心执行部件，其工作性能直接决定播种精度、粒距均匀性、种子出苗率与作物产量。为系统梳理精量排种器技术演进与研究现状，本文针对机械式精量排种器存在的充种效率低、清种效果差、高速作业稳定性不足及田间振动干扰显著等问题，以及气力式精量排种器面临的小籽粒精量播种困难、风压损耗大、气密性与型孔易堵塞等技术瓶颈，分别综述结构创新、机理分析、参数优化与性能提升的最新研究进展；对比分析两类主流排种器的技术优势与适用场景，展望了精量排种器向高速高效、通用适配、智能监测、低损节能方向的发展趋势，为精量播种装备优化设计与技术升级提供了参考。

INTRODUCTION
Precision seeding is a key technology for precision agriculture to save costs, increase efficiency, and ensure uniform seedling emergence. It enables single-grain precision sowing, quantitative positioning, reduced production costs, and significantly improved land utilization and crop yield (*Liao et al., 2025*). As the core functional component of a precision seeder, the seed metering device undertakes the processes of seed storage, seed filling, seed clearing, seed carrying, and seed delivery. Its structural design, working mechanism, and dynamic performance directly affect seeding quality and operational reliability (*Singh et al., 2020*). Precision seed metering devices can be classified into three types based on power source and working principle: mechanical, pneumatic, and electric. Among them, the mechanical and pneumatic types are currently the mainstream applications, while the electric type is still in the experimental and gradual promotion stage (*Ren et al., 2021; Li et al., 2026*). As the present review focuses on the two dominant categories for which sufficient field performance data are available in the published literature, electric-driven seed metering devices were not systematically covered.

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As precision agriculture advances toward higher operational speeds and intelligent control, conventional seed metering devices have progressively failed to satisfy modern agronomic demands, particularly in terms of high-speed adaptability, seed versatility, small-seed precision, vibration resistance, and energy efficiency (*Ren et al., 2026; Li et al., 2026*).

Recent system-level syntheses have identified the speed–precision paradox as a coupled phenomenon in which placement accuracy degrades non-linearly beyond architecture-specific thresholds. A three-regime model was proposed: Regime 1 (<10 km/h) where metering-stage singulation quality governs precision; Regime 2 (10–14 km/h) where delivery-stage instabilities are amplified; and Regime 3 (>14 km/h) where vibration, control latency, and soil–machine interactions dominate system-level breakdown (*Hussain et al., 2026*). This framework provides a unified reference for interpreting speed-dependent performance across mechanical and pneumatic architectures.

In recent years, researchers worldwide have conducted extensive studies on seed filling mechanisms, seed clearing and damage prevention, airflow field optimization, vibration suppression, and intelligent detection of seed metering devices, achieving a series of innovative results *(Liu et al., 2026; Li et al., 2026)*. This review was conducted by searching Web of Science, CNKI, and Scopus databases using keywords "precision seed metering", "mechanical seed metering", and "pneumatic seed metering" for publications from 2000 to 2026. A total of 162 papers were initially identified, of which 80 were selected based on relevance to structural design and performance evaluation. For the quantitative comparison tables (Tables 2, 4, and 5), performance ranges were synthesized from the reviewed literature. The reported values represent representative intervals compiled from reported experimental results, reflecting typical operating conditions across multiple studies. These ranges are intended for comparative illustration rather than absolute performance benchmarking. This paper reviews the technical bottlenecks, solutions, and research progress of mechanical and pneumatic precision seed metering devices, clarifies existing problems and breakthrough paths, and discusses future development trends, aiming to provide a theoretical basis and technical reference for the design optimization, performance improvement, and engineering application of precision seed metering devices.

RESEARCH STATUS OF MECHANICAL-TYPE SEED METERING DEVICES

Mechanical-type seed metering devices rely on mechanical structure differentiation and the combination of gravity and mechanical force to complete seed filling, seed clearing, and seed delivery, without the need for air source assistance *(Li et al., 2020)*. They offer advantages such as simple structure, low manufacturing cost, stable operation, and convenient maintenance, and are widely used in small and medium-sized fields and hilly mountainous areas in China.

Research on precision seeding technology in China began in the 1970s. After stages of structural imitation, independent innovation, and performance optimization, mature structures such as disc type (*Li et al., 2022*), wheel-scoop type (*Su et al., 2022*), chain-scoop type (*Zhang et al., 2023; Dun et al., 2022*), indented wheel type (*Lu et al., 2023; Liu et al., 2016*), and finger-clip type (*Wang et al., 2015*) have been developed, which are suitable for sowing corn, soybean, wheat, coarse cereals, and small-seeded cash crops.

Overseas research on precision seeding technology began in the 1940s, with Germany and the United States as representative countries (*Lai et al., 2022*). The focus was on developing highly reliable structures such as the finger-clip type and the inclined disc type, which have significant advantages in high-speed seeding of large-seeded crops (*Barut et al., 2004*). To address the drawbacks of the finger-clip type precision seed metering device, the German company Schmotzer developed an inclined disc type precision seed metering device. This type of metering device is installed obliquely at the bottom of the seed box. Seeds rely on their own gravity to enter the holes laterally to complete seed filling, and then fall into the seed furrow as the disc rotates. This metering device has a simple structure and low seed damage rate. It is suitable for seeds with regular shape and good flowability, and has strong adaptability to round seeds such as soybean and peanut. However, flat seeds have poor flowability and are prone to jamming, leading to miss-seeding. Based on this type of metering device, *Anantachar et al. (2011)* used an artificial neural network to optimize the seeding performance parameters of the inclined disc type metering device, establishing a relationship model among seeding speed, vegetable seed spacing, and seed damage rate. *Yadachi et al. (2013)* investigated the relationship between the continuous seed filling capacity of carrot seeds and the inclined disc angle. Through comparative experimental analysis, they determined that an inclination angle of 50° was most suitable for seeding carrot seeds.

Grewal et al. (2015) studied the seeding performance of an inclined disc onion seeder under different rotational speeds and different numbers of grooves/holes, evaluating the machine using the qualified seeding index, multiple-seeding index, and miss-seeding index, and obtained satisfactory results. *Van Loon et al. (2020)* conducted a cross-continental comparative study of ten mechanical maize seed metering devices from Latin America, Sub-Saharan Africa, and Asia, identifying 20 RPM as the optimal rotational speed across device types and demonstrating that adjustable-hole metering devices consistently outperformed fixed-hole designs in terms of seeding quality and operational flexibility.

Table 1

Mechanical-type precision seed metering devices: types, features and representative crops

(Synthesized from Geng et al., 2016, 2018; Su et al., 2022; Li et al., 2022; Lu et al., 2023; Liu et al., 2016; Wang et al., 2015; Dun et al., 2022)

Type	Main Features	Representative Crops
Disc type	Hole shape determines seed size; hole spacing, together with travel speed, plate rotational speed, transmission ratio, seed bounce, and delivery dynamics, collectively determines plant spacing. Simple structure but limited versatility.	Corn, soybean
Wheel-scoop type	Simple and durable structure, but requires changing the seed scoop to adapt to different seeds.	Sorghum, *Pinellia ternata* (banxia), potato
Indented wheel type	Strong power adaptability but poor seed adaptability. Generally used for seeds with relatively spherical shape and high roundness.	Soybean, rapeseed
Finger-clip type	Relatively stable operational performance, but complex structure and limited versatility.	Corn, *Cyperus esculentus* (tiger nut)

Note: Structural schematic diagrams have been omitted for brevity. For detailed structural illustrations, please refer to the original cited references.

Mechanical-type seed metering devices have the advantages of simple structure, low cost, and reliable operation, but they still suffer from the following problems:

(1) Limited seed filling efficiency: The hole shape must closely match the seed geometry. Under high-speed operation, seed filling is insufficient, leading to an increased miss-seeding rate.

(2) Prominent seed clearing contradiction: Relying on gravity for seed clearing tends to cause multiple-seeding, while relying on rigid components for seed clearing tends to cause seed damage and jamming.

(3) Poor high-speed and vibration resistance: When the operating speed reaches 6 km/h or higher, seed spacing uniformity deteriorates, and field vertical vibration significantly interferes with seeding stability. However, this threshold is device-specific; for example, in a finger-clip type corn seed metering device, seed spacing uniformity was found to deteriorate significantly when operating speed exceeded 6 km/h (*Wang et al., 2019*), whereas newer designs with disturbance-assisted mechanisms have extended this limit substantially.

Rapid seed filling and stable seed delivery

To address the problems of insufficient seed filling and disordered seed delivery under high-speed operation, domestic and overseas scholars have improved performance through structural improvement, mechanical modeling, and parameter optimization. *Huang et al. (2022)* added a guide plate and a lateral double-fixing structure, which shortened the seed delivery path and achieved a qualified seeding rate of >95.27% at operating speeds of 4–14 km/h. *Liu et al. (2016)* proposed an opposed swash plate structure, established a seed filling mechanical model, and determined that the seed filling effect for soybean was optimal at an inclination angle of 20°. *Li et al. (2018)* designed a cone-disc centrifugal pushing structure, which reduced the miss-seeding rate by 2.52% at operating speeds of 7–13 km/h. *Correia et al. (2016)* showed through experiments that moderately increasing the inclination angle of the seed metering device and increasing the working rotational speed could reduce seed accumulation in the chamber and improve the stability of seed filling and seed delivery.

Dong et al. (2025) introduced a posture-adjusting seed metering device for high-speed maize planting, in which seed-filling posture was adjusted and the seed group was fluidized through groove-type structures. EDEM simulation and bench testing demonstrated that the optimized device achieved pass, repeat, and miss rates of 94.8%, 1.3%, and 3.9%, respectively.

Within the speed range of 8–14 km/h, the pass rate consistently exceeded 94%, with repeat rate below 2.1% and miss rate below 3.9%, substantially outperforming devices without posture-adjusting mechanisms.

For rice mechanical seeding, *Zhang et al. (2025)* calibrated DEM contact parameters using a multi-sphere rice model, achieving prediction errors of less than 0.13% for miss-seeding, qualified, and re-seeding rates, demonstrating the effectiveness of DEM-based virtual design for non-spherical seeds. *Zheng et al. (2025)* designed a screw-guided posture-adjusting and filling-promoting precision seed metering device for wheat, establishing a mechanical model of seed posture adjustment under the combined action of spiral guidance and gravity. The device achieved a qualified seeding rate exceeding 90% within a working speed range of 30–70 r/min, providing an effective solution for precision seeding of small-sized cereal seeds.

Poor performance of the seed clearing zone

The seed clearing stage is key to reducing multiple-seeding and minimizing seed damage. *Zhang et al. (2021)* determined through force analysis that the minimum clearance of 1.47 mm in a dual-chamber vertical disc metering device is the critical damage threshold for cotton seeds, with damage occurring when the clearance was less than this threshold, whereas no significant damage was observed above this value under the tested conditions. The study clarified the order of influence of rotational speed, clearance, and installation angle on the damage rate. *Zhang et al. (2014)* replaced the seed guard plate with flexible rubber, reducing the seed damage rate by 0.6%. *Zhou et al. (2018)* established a shear damage model and reduced the breakage rate by constraining the hole length to avoid the shear zone. *Ryu and Kim (1988)* employed methods such as brush clearing and flexible scraping to reduce mechanical damage while ensuring clearing effectiveness.

Effect of vibration on seed metering performance

When a seeder operates in the field, random vibrations are generated due to factors such as soil structure and surface unevenness. Among these, the vertical vibration during forward motion is particularly significant, leading to reduced seeding performance and affecting subsequent crop growth and yield. *Wang et al. (2019)* established a vibration model of a finger-clip type seed metering device and confirmed that vibration has a significant effect on the qualified seeding rate and the coefficient of variation of seed spacing. Vibration experiments were conducted at frequencies of 5–20 Hz and amplitudes of 2–10 mm, based on field measurements from tillage operations. *Li (2022)* combined high-speed photography with trajectory equations to identify the key vibration parameters affecting seed delivery uniformity. *Huang et al. (2021)* revealed the coupled effects of vibration amplitude, frequency, and operating speed on the wheel-scoop type seed metering device, providing a theoretical basis for anti-vibration design. The interaction between vibration and seed metering performance has been further quantified through DEM-based sensitivity analysis. *Zhang et al. (2025)* identified inter-particle static and rolling friction coefficients as the dominant DEM contact parameters affecting rice seed metering, with optimal values of 0.445 and 0.059, respectively. The validation tests confirmed that errors between simulation and bench tests remained below 1.4% for seed number frequency per seeding hole, providing a calibrated modeling approach for evaluating vibration-induced performance degradation.

Table 2

Quantitative comparison of mechanical-type seed metering device performance across key metrics

(Synthesized from Anantachar et al., 2011; Barut and Özmerzi, 2004; Correia et al., 2016; Dong et al., 2025; Dun et al., 2022; Geng et al., 2016, 2018; Grewal et al., 2015; Huang et al., 2021, 2022; Kachman and Smith, 1995; Karayel, 2009; Li et al., 2018, 2020, 2022; Liu et al., 2016; Ryu and Kim, 1988; Su et al., 2022; Van Loon et al., 2020; Wang et al., 2015, 2019; Zhang et al., 2014, 2021, 2025; Zheng et al., 2025; Zhou et al., 2018)

Performance Metric	Disc Type	Wheel-Scoop Type	Indented Wheel Type	Finger-Clip Type
Typical operating speed	4–8 km/h	4–7 km/h	5–9 km/h	6–10 km/h
Qualified index	88–93%	85–90%	90–95%	92–96%
Miss index	3–7%	5–10%	2–5%	2–4%
Multiple index	3–6%	3–8%	2–5%	2–5%
Seed damage rate	0.5–1.5%	0.3–1.0%	0.3–0.8%	0.4–2.0%

Performance Metric	Disc Type	Wheel-Scoop Type	Indented Wheel Type	Finger-Clip Type
Seed adaptability	Poor	Medium	Poor	Medium
Structural complexity	Low	Low	Medium	High
Manufacturing cost	Low	Low	Medium	High

Note: Values represent representative ranges compiled from the cited references based on the authors' synthesis of reported experimental results. The ranges reflect typical operating conditions reported across multiple studies and are intended for comparative illustration rather than absolute performance benchmarking. Specific performance may vary with seed type, rotational speed, operating pressure, and other conditions.

RESEARCH STATUS OF PNEUMATIC-TYPE SEED METERING DEVICES

Pneumatic-type seed metering devices use positive/negative pressure generated by a fan to achieve seed suction, seed carrying, and seed delivery. They have low requirements on seed shape and size, low seed damage rate, high operating speed, and wide adaptability to seed varieties. They are the mainstream configuration for large and medium-sized high-speed precision seeders, and are mainly divided into four categories: air-suction type, air-blowing type, positive/negative pressure combined type, and central pneumatic delivery type.

Bustos-Gaytán et al. (2025) systematically reviewed experimental and numerical simulation approaches for pneumatic seed-metering devices, finding that 86% of studies focused on air-vacuum systems while only 14% addressed air-blowing systems. Numerical tools including CFD, DEM, and coupled CFD–DEM were identified as crucial for optimizing air chamber geometry, seed plate hole shapes, and seed-cleaning device designs. However, fewer studies have focused on seed-cleaning and anti-blocking devices, indicating a research gap.

With the development of mechanical-type seed metering devices, in the 1950s, many overseas scholars combined mechanical structure theory with fluid mechanics to investigate the effects of airflow pressure and direction on the various states of materials within mechanical structures, leading to the invention of pneumatic-type precision seed metering devices. By the 1960s, pneumatic-type precision seed metering devices had begun to be used and promoted, and countries with advanced agricultural systems, such as the United States and Germany, had developed various types of pneumatic seeders. In the 1980s, the new concept of pneumatic precision seeding reached international consensus. After years of development, operating speed and seeding quality have continuously improved, but still cannot meet the ever-increasing agronomic requirements, prompting European and American countries to vigorously develop precision seeding technology, thus leading to the widespread application of pneumatic-type precision seed metering devices. With technological advancement, precision seeding technology has become increasingly mature and is moving towards the direction of precision, high speed, automation, and intelligence, offering advantages such as compact structure and excellent performance (*Karayel, 2009*). Overseas pneumatic-type precision seed metering devices are mainly used for crops such as corn, soybean, and rice, while also serving vegetable seeding. Compared with mechanical-type seed metering devices, pneumatic-type precision seed metering devices have the advantages of less seed damage, wide adaptability, high operating speed, and good seeding performance. They have developed relatively quickly and gradually occupied a mainstream position. At present, pneumatic-type precision seed metering devices are relatively well-developed abroad, but their adaptability to small-sized vegetable seeds still needs improvement.

Table 3

Pneumatic-type precision seed metering devices: types, features and representative crops

(Synthesized from Bustos-Gaytán et al., 2025; Fang et al., 2024; Gao et al., 2022; Guo et al., 2024; Karayel, 2009; Li et al., 2023; Liu et al., 2022; Sun et al., 2025; Wang et al., 2019, 2026; Yan et al., 2017; Yang et al., 2022; Yatskul et al., 2017; Yi et al., 2021; Zha et al., 2024; Zhang et al., 2019)

Type	Main Features	Representative Crops
Air-suction type	Moderate seed adaptability (excellent for large seeds, challenging for seeds <3 mm); high requirements on airtightness; high fan power consumption (depending on system scale and operating pressure); capable of high-speed seeding. Typical negative pressure: 3–6 kPa.	Corn, soybean, vegetables

Type	Main Features	Representative Crops
Air-blowing type	Simple and durable structure; uses positive pressure airflow to assist seed filling and clearing; seed adaptability is improved by adjusting air pressure rather than changing mechanical components. Typical positive pressure: 2–4 kPa.	Sorghum, *Panax notoginseng*
Positive/negative pressure combined type	Generates lower air pressure than the air-suction type; low seed damage rate; good versatility; operating speed ≤8 km/h. Typical negative pressure: 2–4 kPa; positive pressure: 1–2 kPa.	Rapeseed, pak choi
Central pneumatic delivery type	Strong seed adaptability and easy seed filling, suitable for a wide range of crop types including cereals, rapeseed, and other small-to-medium seeds; high miss-seeding index at medium and high speeds requires further optimization.	Cereals, rapeseed, small-to-medium seeds

Note: Structural schematic diagrams have been omitted for brevity. For detailed structural illustrations, please refer to the original cited references.

Pneumatic-type precision seed metering devices are widely used on large and medium-sized seeding equipment in large-scale planting areas due to their low requirements on seed shape and size, good seeding quality, and high operating speed. *Guo et al. (2024)* systematically analysed four key technologies limiting the operational speed improvement of pneumatic seed metering devices: high-speed seed filling technology, stable seed clearing technology, smooth seed delivery control technology, and stable driving technology of the metering device, identifying stable filling, effective clearing, and smooth delivery as the core measures for effectively improving the qualified seeding rate and reducing the coefficient of variation at high speeds. However, they still have some problems:

(1) Multiple-seeding and miss-seeding: High-speed operation leads to airtightness fluctuations, hole clogging, and seed population dragging, resulting in reduced stability *(Zhang et al., 2019)*.

(2) Difficulty in seeding small seeds: Seeds with a particle size of less than 3 mm are light in weight and sensitive to negative pressure, requiring stringent hole geometry and air pressure parameters.

(3) Large air pressure loss: Seal wear and air leakage between chambers lead to increased energy consumption and degradation of metering performance.

Control of multiple-seeding and miss-seeding

To address the problems of multiple-seeding and miss-seeding caused by internal airtightness fluctuations, hole clogging during seed filling and seed clearing, and seed population dragging in pneumatic-type precision seed metering devices during high-speed operation, *Önal et al. (2012)* optimized the airtightness of the air chamber using fluid mechanics and aerodynamics, effectively solving the issue of unstable airflow fields during seed filling for cotton and corn seeds. *Jia et al. (2018)* adopted an air-suction mechanical composite picking mechanism to reduce the interference of sudden negative pressure drops on soybean seeding. *Li et al. (2010)* proposed a seeding frequency method to detect hole clogging in a pneumatic-type precision seed metering device for rapeseed. *Yang (2020)* added grooves and seed disturbing teeth on the suction plate to suppress rapeseed population dragging and reduce miss-seeding. *Wang et al. (2019)* designed a flexible vibrating seed metering belt to achieve high-speed single-seed suction for soybean, and obtained the optimal operating parameters of the metering device through experiments.

Sun et al. (2025) designed a progressive seed-cleaning mechanism for an air-pressure maize precision seed metering device, establishing mechanical models for excess seeds entering the cleaning zone. Through single-factor and multi-factor experiments, the optimal parameter combination was determined as: seed-clearing angle of 0.024°, operating speed of 10 km/h, and positive pressure of 6.0 kPa. Under these conditions, the qualified index reached 98.11%, multiple index 1.44%, and miss index 0.45%. Comparative experiments demonstrated that the device with the seed-cleaning mechanism improved the qualified index by approximately 2.3 percentage points compared to the device without the mechanism. *Wang et al. (2026)* designed and optimized a combined seed cleaning mechanism for an air-suction seed metering device for small-seed crops with multi-seed hill, achieving significantly improved cleaning performance through structural optimization.

Zhang et al. (2019) conducted optimal design and experiments on a double-disc air-suction precision seed metering device with variable hole diameter, demonstrating that the device successfully adapted to six types of vegetable seeds by rotating and combining to produce different hole diameters under negative pressure conditions.

Precision seeding technology for small-sized seeds

For small-sized seeds such as sesame, millet, rapeseed, and vegetables, technologies including negative pressure suction combined with positive pressure seed delivery, variable-diameter holes, and photoelectric detection have been adopted both domestically and internationally. *Yi et al. (2021)* and *Gao et al. (2022)* each designed pneumatic-type precision seed metering devices for millet and rapeseed, respectively, using the principle of negative pressure suction and positive pressure seed delivery. *Li et al. (2018)* proposed a beam-blocking method to detect insufficient filling and hole clogging in pneumatic-type precision seed metering devices, achieving precision seeding detection for white radish, rapeseed, and Shanghai bok choy seeds. *Li (2019)* designed a precision seed metering device capable of rotating and combining to produce different hole diameters under negative pressure conditions, adapting to six types of vegetable seeds. *Liao et al. (2018)* investigated the factors affecting the suction effect of spherical small-sized seeds such as rapeseed and Chinese cabbage, established a critical pressure model for seed suction, and clarified the coupling relationship among thousand-seed weight, hole diameter, and negative pressure.

For rice seeding, *Zha et al. (2024)* developed a branched air-chamber pneumatic seed metering device capable of adjusting seeding quantity from 1–3 to 5–8 seeds per hill by controlling the branched air chamber casing. Bench tests showed optimal qualification rates of 85.81% for 1–3 seeds/hole and 87.27% for 5–8 seeds/hole. *Fang et al. (2024)* integrated image recognition and orientation technology into an air-suction garlic seed metering device, achieving single-seed rates of 95.98%–96.23% under optimized parameters including negative pressure of 11.85–13.21 kPa and rotational speed of 6.85–7.25 r/min. *Zhao et al. (2024)* provided a comprehensive analysis of rice precision direct seeder seed metering devices, identifying the improvement path for air-suction precision: improving seed flowability, stabilizing negative pressure, and adjusting seed posture to enhance singulation accuracy. *Li et al. (2023)* optimized design parameters for a pneumatic hill-drop rapeseed metering device, determining that optimal performance was achieved at hole velocity of 30–70 r/min and negative pressure of –2.5 to –1.5 kPa, with miss-seeding rate consistently below 3%.

Suppression of air pressure loss

The susceptibility to wear of the sealing gasket between the seed plate and the negative pressure chamber of an air-suction type precision seed metering device is the main cause of air pressure loss *Yan et al. (2017)*. *Yan et al. (2017)* and Kverneland AS have both adopted a design where the seed plate and the negative pressure chamber rotate synchronously, thereby reducing sealing gasket wear, decreasing air pressure loss, and ensuring metering performance. On this basis, *Yan et al. (2017)* modified the seed plate into an annular frustum shape, achieving lower air pressure demand and energy consumption compared to Kverneland's design. To address the issue of significant air pressure loss caused by multiple seeding units sharing a common air chamber in air-suction type precision seed metering devices, *Li et al. (2023)* designed an independent grooved airway disc, enabling independent air supply to each row and reducing cross-leakage losses. *Wang et al. (2022)* analysed the mixing device of a central pneumatic delivery type seed metering device and indicated that the greater the amount of seeds being conveyed and the higher the seed-to-airflow ratio, the larger the air pressure loss in the mixing component.

Mechanical-pneumatic hybrid systems

Hao et al. (2026) designed and validated a mechanical-pneumatic hybrid metering device for mixed seeding of forage seeds, combining the simplicity of mechanical seed picking with the conveying capability of pneumatic assistance. The device achieved relative seeding errors of 6.81%–7.49% for mixed forage seed applications, demonstrating the feasibility of hybrid architectures for multi-species seeding operations where seed geometry and physical properties vary significantly among species. *Tang et al. (2023)* designed a high-speed precision seed metering device with air-assisted seed guide (inside-filling air-blowing type), achieving improved seed trajectory stability and placement accuracy through controlled airflow guidance.

Table 4

Quantitative comparison of pneumatic-type seed metering device performance across key metrics

(Synthesized from Bustos-Gaytán et al., 2025; Fang et al., 2024; Gao et al., 2022; Guo et al., 2024; Hussain et al., 2026; Jia et al., 2018; Li et al., 2010, 2023; Liu et al., 2022; Maleki et al., 2006; Önal et al., 2012; Sun et al., 2025; Wang et al., 2019, 2022, 2026; Yan et al., 2017; Yang et al., 2022; Yatskul et al., 2017; Yi et al., 2021; Zha et al., 2024; Zhang et al., 2019)

Performance Metric	Air-Suction Type	Air-Blowing Type	Positive/Negative Pressure Combined Type	Central Pneumatic Delivery Type
Typical operating speed	8–14 km/h	6–10 km/h	≤8 km/h	6–12 km/h
Qualified index	95–98%	90–95%	92–96%	88–93%
Miss index	2–5%	3–7%	2–5%	5–10%
Multiple index	2–5%	3–6%	2–4%	3–8%
Seed damage rate	＜0.5%	＜0.5%	＜0.3%	1–3%
Seed adaptability	Excellent	Good	Good	Excellent
Air pressure loss	High	Medium	Low	High
Fan power consumption	High (depending on system scale and operating pressure)	Medium (2–3 kW/row)	Low (1–2 kW/row)	High

Note: Values represent representative ranges compiled from the cited references based on the authors' synthesis of reported experimental results. The ranges reflect typical operating conditions reported across multiple studies and are intended for comparative illustration rather than absolute performance benchmarking. Specific performance may vary with seed type, rotational speed, operating pressure, and other conditions.

Table 5

Cross-type comparative analysis of mechanical versus pneumatic seed metering devices

(Synthesized from Bustos-Gaytán et al., 2025; Dong et al., 2025; Guo et al., 2024; Hussain et al., 2026; Karayel, 2009; Van Loon et al., 2020; Wang et al., 2019; Yang et al., 2022; Zhang et al., 2019)

Comparison Dimension	Mechanical Type	Pneumatic Type
Maximum stable operating speed	6–10 km/h	8–14 km/h
Qualified index (typical)	85–96%	88–98%
Seed adaptability	Poor–Medium	Good–Excellent
Seed damage rate	0.3–2.0%	<0.5%
Unit energy consumption (relative)	Low (~90 kJ/ha)	High (~6,400 kJ/ha for full pneumatic)
Centrifugal vs. pneumatic power ratio	—	1:71 (centrifugal consumes 1/71 of pneumatic)
Structural complexity	Simple	Complex
Manufacturing cost	Low	High
Operating speed increase trend	Optimized designs reaching 13–14 km/h with >94% qualified index	Clear speed–precision trade-off beyond 14 km/h
Suitable operation scale	Small-to-medium fields, hilly terrain	Large-scale plain farming
Vibration sensitivity	High	Medium
Airtightness requirement	None	Critical

Note: Values represent representative ranges compiled from the cited references based on the authors' synthesis of reported experimental results. The ranges reflect typical operating conditions reported across multiple studies and are intended for comparative illustration rather than absolute performance benchmarking. Specific performance may vary with seed type, rotational speed, operating pressure, and other conditions.

The cross-type comparison presented in Table 5 is intended to illustrate general performance trends and architectural trade-offs rather than to establish precise performance rankings. The reported ranges are compiled from multiple studies with varying experimental conditions. Actual performance comparisons should be interpreted with consideration of operating parameters and test standards.

DEVELOPMENT TRENDS

Mechanism-based and precision-oriented

Deepen the research on the multi-field coupling mechanism of seed–structure–airflow–vibration, and establish a full-cycle dynamic model. Employ simulation tools such as EDEM and CFD to achieve multi-objective optimization of structural and operating parameters. *Bustos-Gaytán et al. (2025)* confirmed that CFD-DEM coupling has become the essential tool for optimizing pneumatic metering components, yet seed-clearing and anti-blocking devices remain understudied. Develop a unified performance evaluation system to enhance the standardization level of seed metering device design, testing, and application. The speed–precision paradox framework provides a quantitative basis for defining architecture-specific performance envelopes and identifying optimal operating windows for different device types.

Lightweight and adaptable

For scenarios such as hilly and mountainous areas and facility agriculture, develop lightweight, miniaturized, and modular seed metering devices to improve adaptability to mountainous regions and small plots. Optimize structural materials and manufacturing processes to reduce cost, extend service life, and simplify maintenance. Promote the integration of mechanical and pneumatic technologies, combining the reliability of mechanical structures with the versatility of pneumatic systems, to form low-cost, high-performance composite seed metering technology. The mechanical-pneumatic hybrid approach demonstrated by *Hao et al. (2026)* offers a promising pathway for multi-species and mixed-seeding applications where seed physical properties vary considerably.

Intelligent and visualized

Integrate machine vision, photoelectric sensing, microcontroller, and virtual instrument technologies to achieve online monitoring of the seeding process, real-time alarming for miss-seeding, clogging, and multiple-seeding, and automatic adjustment of seeding rate. Build a digital twin system for seeding performance to enable visualized simulation and prediction of seed filling, seed clearing, airflow field, and vibration response. *Guo and Zhao* (*2026*) systematically reviewed edge-intelligent precision seeding monitoring and control technologies, identifying photoelectric, fibre-optic, and infrared-based methods as relatively mature in engineering applications. Capacitive, piezoelectric, near-infrared, laser-based, and machine vision methods offer advantages in detection accuracy and information richness, yet face challenges in system complexity, edge-side deployment, and long-term robustness. Future intelligent precision seeding technology was projected to develop toward multi-source heterogeneous information fusion, low-latency closed-loop control, standardized data sharing, and farm-level quality evaluation. Develop fault self-diagnosis and parameter self-optimization systems to enhance the reliability of the entire seeding process.

CONCLUSIONS

This systematic review of mechanical-type and pneumatic-type precision seed metering devices yielded the following synthesized findings.

Mechanical-type seed metering devices, including disc, wheel-scoop, indented wheel, and finger-clip types, offer advantages of simple structure, low manufacturing cost, and high reliability, making them suitable for small-to-medium sized fields and hilly terrain. However, their performance is constrained by architecture-specific thresholds: seed filling efficiency decreases significantly when operating speed exceeds 6–8 km/h, and seed spacing uniformity deteriorates under field vibration. Recent innovations, including disturbance-assisted filling mechanisms, screw-guided posture adjustment, and posture-adjusting metering devices, have extended stable operation to 13 km/h with qualified rates exceeding 94%. Cross-continental comparative testing has demonstrated that adjustable-hole metering devices consistently outperform fixed-hole designs, providing a practical pathway for improving mechanical device versatility.

Pneumatic-type seed metering devices, comprising air-suction, air-blowing, positive/negative pressure combined, and central pneumatic delivery types, demonstrate superior seed adaptability and high-speed capability. Nevertheless, 86% of research has focused on air-suction systems, while seed-cleaning and anti-blocking devices remain understudied. Key challenges include small-seed (<3 mm) precision seeding, air pressure loss from seal wear, and hole clogging at elevated speeds. Recent advances in progressive seed-cleaning mechanisms and branched air-chamber designs have substantially improved performance, with qualified indices exceeding 98% achieved under optimized conditions.

Table 6

Comparative decision framework for selecting seed metering device types

Operating Condition	Recommended Type	Rationale
Speed ≤8 km/h, uniform seed geometry, cost-sensitive	Mechanical	Lower cost, sufficient accuracy, simple maintenance
Speed ≥8 km/h, irregular seed shapes, large-scale	Pneumatic	Higher speed capability, better seed adaptability
Multi-species mixed seeding	Hybrid (mechanical-pneumatic)	Combines picking simplicity with conveying versatility
Small seeds (<3 mm), high precision requirement	Pneumatic with optimized hole/negative pressure	Superior singulation when properly tuned

Quantitative conclusions indicate that pneumatic systems typically achieve qualified indices 5–10 percentage points higher than mechanical types at speeds >8 km/h, at the cost of substantially higher energy consumption. Notably, recent system-level analysis reported that centrifugal metering systems consume approximately 71 times less power than full pneumatic systems under comparable single-row operating conditions. However, this comparison is based on a specific system configuration and operating point; the actual power ratio depends on factors including system scale, operating pressure, number of rows, and seed characteristics. The reported value should be interpreted as an indicative comparison for a reference operating condition rather than a universal constant.

The speed–precision paradox follows a three-stage pattern: Regime 1 (<10 km/h) where metering-stage singulation quality governs precision; Regime 2 (10–14 km/h) where delivery-stage instabilities are amplified; and Regime 3 (>14 km/h) where vibration, control latency, and soil–machine interactions dominate system-level breakdown.

Limitations of this review include: (1) electric-driven seed metering devices were not systematically covered due to limited published field data; (2) quantitative comparative analysis was constrained by inconsistent reporting of performance parameters across studies; and (3) the review primarily focused on English and Chinese language publications, potentially omitting relevant studies in other languages, although English-translated titles were provided for all Chinese references to ensure accessibility. Future research should deepen multi-field coupling mechanisms and integrate mechatronic technologies to promote high-efficiency, adaptive, and intelligent development of precision seed meters for modern agriculture.

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