Research progress on mechanized garlic seeding technology in China

Mingxi Shao[1,3], Xiumei Zhang[2], Lizhi Fang[3], Guocai Ma[1], Jie Tian[1,4], Shenghui Fu[3*]
(1. *Qinghai University, Xining 810016, China*;
2. *Weifang University of Science and Technology, Weifang 262700, China*;
3. *College of Mechanical and Electronic Engineering, Shandong Agricultural University, Tai'an 271018, China*;
4. *Qinghai Key Laboratory of Vegetable Genetics and Physiology, Academy of Agriculture and Forestry Sciences of Qinghai University, Xining 810016, China*)

Abstract: Garlic is a traditional vegetable and an important horticultural crop in China, with its cultivated area and production ranking first among all countries in the world. In recent years, with social and economic development, labor costs have generally risen, which has directly led to the cost of garlic planting rising year after year, the decline in profits from garlic planting, and the continued reduction in garlic planting area. In this review, the development of mechanized planting in the main garlic-producing countries in the world is discussed in detail, and the present situation and characteristics of mechanized planting in China are analyzed. The advanced garlic seeding machinery and existing problems are compared and investigated, and the development status and technical characteristics of garlic seeding mechanization in China are analyzed. On this basis, it is pointed out that China's garlic sowing mechanization faces the problems of insufficient integration of agricultural machinery and agronomy, lack of unification of planting mode, and imperfection of core functions. In addition, relevant suggestions are put forward for the problems faced by China's mechanical garlic sowing equipment: develop garlic sowing mechanization equipment according to local conditions, promote standardized garlic planting agronomy, improve the innovation ability of core components, and develop a garlic seeder to meet the agronomic requirements of the country.

Keywords: garlic, seeding machinery, seeding agronomy, single-seed sowing device, orientation of garlic clove bud
DOI: 10.25165/j.ijabe.20251802.9035

Citation: Shao M X, Zhang X M, Fang L Z, Ma G C, Tian J, Fu S H. Research progress on mechanized garlic seeding technology in China. Int J Agric & Biol Eng, 2025; 18(2): 9–20.

1 Introduction

As a traditional vegetable and an important horticultural crop in China, garlic ranks first in the world in terms of cultivated area and production. This common condiment not only imparts unique flavor and aroma to dishes, but also plays an important role in healthcare. Garlic is rich in biologically active components such as allicin and sulfur compounds, which have a variety of antibacterial, anti-inflammatory, and antioxidant properties[1-5]. Studies have shown that garlic also has some preventive and therapeutic potential for health problems such as cardiovascular diseases, colds, hypertension, and hyperlipidemia[6,7]. In addition, some studies have indicated that specific components of garlic may have inhibitory effects on cancer and are expected to play an important role in the prevention and treatment of cancer[8-10].

Garlic production and consumption in China perennially ranks first in the world. In recent years, with continuous social and economic development, the planting costs of fertilizers and pesticides have increased, and the cost of labor has generally risen, which has directly led to the total cost of garlic cultivation rising year after year. As a result of this impact, garlic planting profits have declined, and the planting area has continued to decrease. Statistics show that in 2021, China's total garlic production exceeded 20 million t, but in 2023, garlic production fell to about 7 million t, a drop of more than 60%. In the planting cost structure, labor cost accounts for 30%-40% of the total cost, making it the most expensive of all costs. The main reason for the high labor cost is the high agronomic requirements of domestic garlic planting, which leads to the low level of mechanization development and low per capita cultivation efficiency in China. Therefore, there is an urgent need to develop a garlic seeding machine with high stability and fast operating speed in the field of garlic cultivation in China[11,12].

In this paper, the development of mechanized planting of garlic throughout the world is discussed in Section 2, and the present situation of mechanized planting and the characteristics of garlic planting in China are analyzed. The more advanced garlic planters at home and abroad and existing problems are compared and investigated in Section 3. In Section 4, the main agronomic requirements of garlic in China are analyzed, the current development status and key technologies of garlic sowing mechanization are discussed in detail, and three key technical problems facing garlic planters are pointed out. Moreover, the problems facing the mechanization development of garlic planting in China are pointed out, and development suggestions are put forward in Section 5. Finally, the conclusion is summarized in Section 6.

Received date: 2024-04-28 **Accepted date:** 2025-02-25
Biographies: Mingxi Shao, PhD, Lecturer, research interest: intelligent agricultural machinery equipment, Email: nifengfeiyang@163.com; **Xiumei Zhang**, MS, Associate Professor, research interest: intelligent agricultural machinery equipment, Email: 393488606@qq.com; **Lizhi Fang**, MS candidate, research interest: intelligent agricultural machinery equipment, Email: 814785254@qq.com; **Guocai Ma**, MS, Associate Professor, research interest: image processing and machine learning, Email: maguocai@qhu.edu.cn; **Jie Tian**, PhD, Associate Researcher, research interest: vegetable physiology and molecular biotechnology, Email: tianjie@qhu.edu.cn.
***Corresponding author: Shenghui Fu**, PhD, Associate Professor, research interest: intelligent agricultural machinery equipment. College of Mechanical and Electronic Engineering, Shandong Agricultural University, Tai'an 271018, China, Tel: +86-18811126208, Email: fush@sdau.edu.cn.

2 Statistical analysis of garlic cultivation

2.1 Garlic cultivation worldwide

Garlic is an important cash crop cultivated all over the world[13]. The United Nations Food and Agriculture Organization (FAO) data show that in 2023, the global garlic planting area was more than 0.73 million hm² (11 million mu) and production reached 14.4 million t. The major garlic-producing countries include China, India, Bangladesh, Egypt, and South Korea. As the world's second largest garlic-growing country, India's garlic planting area and production in the global garlic planting area and production accounted for 24.18% and 11.39%, respectively, in 2023, and its garlic is mainly produced in the northern states of Rokhand, Chhattisgarh, and other places. Different countries have different agronomic requirements according to their national conditions. Western developed countries, such as Europe and the United States, have relatively low population density, so the production requirements per unit area are more relaxed. In these regions, garlic planting pays more attention to improving seeding agronomy efficiency and reducing costs, and usually does not take bulb orientation as a focus of attention. Agronomic requirements are relatively easy to meet, which is conducive to the realization of garlic mechanization and large-scale planting. In contrast, South Asia, such as India and Bangladesh, is one of the most densely populated regions in the world. These areas have certain requirements for unit-area yields, but due to the limitations of climatic conditions, agricultural infrastructure, and planting technology, unit-area yields are usually low. In addition, these regions experience a lack of uniform specifications for planting patterns, an insufficient combination of agricultural machinery and agronomy, and a slow process of mechanization of garlic planting. In the Asia-Pacific region, South Korea, for example, is densely populated and has a limited area of arable land, so the yield per unit area is required to be higher, and the domestic garlic planting industry is dominated by intensive cultivation. In recent years, the Korean government has established a number of agricultural technology demonstration centers, and the mechanization level of these demonstration areas is relatively high. However, the overall level of mechanization still needs to be improved due to varietal differences and planting costs in actual production[14].

2.2 Garlic cultivation in China

China is the world's top producer of garlic, ranking first in both production and exports. In 2023, China exported garlic to 165 countries and regions, with a vast international market of which Indonesia, Vietnam, Malaysia, and the United States are the main export markets, with a total export volume of more than 2.2 million t, amounting to more than 3 billion US dollars. China's domestic market demand for garlic is also very huge, with total consumption in 2023 at more than 5 million t, accounting for more than 60% of the total domestic production. Due to the vast planting area of garlic in China and the large population base, the output per unit area is required to be high, and the planting process requires fine management. The planting and agronomy requirements should meet the three indices of single-seed extraction, scale-bud facing up, and vertical insertion. Among these, the scale-bud orientation technology of soft scale-bud hybrid garlic seed is the most difficult; the existing garlic seeding machinery has poor operation effect in this field, and farmers lack trust in seeding machines[15-17].

China's garlic planting industry has obvious geographical aggregation distribution characteristics, as shown in Figure 1. The main producing areas of garlic in China are concentrated in Shandong, Hebei, Henan, and other provinces. Among them, Shandong garlic is the most representative. Jinxiang County in Shandong Province is known as the "Hometown of Garlic in China" for its outstanding garlic quality and perfect garlic industry system, and it occupies a significant share in the total national output.

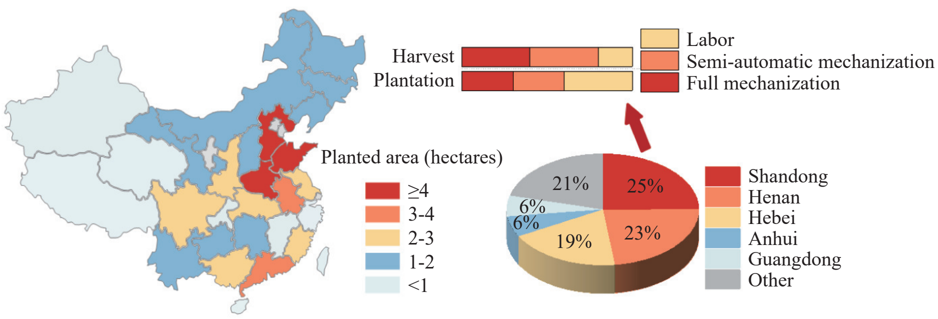

Figure 1 Distribution map of garlic planting area in major provinces of China

Lanling County and Jinxiang County in Shandong Province are important garlic-producing areas, as shown in Figure 2 through the comparison of Jinxiang garlic and Cangshan garlic. The shape of Cangshan garlic is regular, the whole is semicircular, and the size difference is small. The morphology of garlic species is relatively uniform, and there is usually no clamping phenomenon. The end of the scale bud is usually located in the most inner part of the garlic clove, and it is slender and upright with hard texture, and the characteristics of the scale bud are obvious. The center of gravity position is mostly concentrated in the lower part, which is conducive to mechanized sowing and can ensure the upright rate of garlic seeds after planting. Compared with Jinxiang garlic, the inhomogeneity is obvious, the volume difference is large, the shape is irregular, and the clamping phenomenon often occurs. The scale-bud part is weak and soft, and the tip is curved inward. It is difficult to ensure the upright rate of garlic seeds after planting, and it is difficult to achieve effective scale-bud orientation operation with existing seeding machinery.

The varieties of garlic planted in China are diverse and the morphological structure is complex, but the whole can be divided into two categories. One is the Cangshan garlic as the representative of the garlic species. This kind of garlic species' scale bud characteristics are obvious, and the biological form is more regular. The other kind is the garlic species represented by Jinxiang garlic, which has fuzzy characteristics of scale bud and obvious heterogeneity of biological morphology. In order to obtain representative conclusions, the following studies were conducted based on these two kinds of garlic species.

a. Garlic structure of Jinxiang garlic and Cangshan garlic

b. Structure comparison of Cangshan garlic and Jinxiang garlic

Figure 2 Comparison between Cangshan garlic and Jinxiang garlic

3 Research status of garlic planter equipment abroad

3.1 Research status of garlic seeder equipment in Europe and America

In Europe, the United States, and other vast and sparsely populated areas, garlic cultivation mainly adopts the large-scale farm planting mode, which uses random sowing of garlic to ensure operational efficiency. Moreover, garlic is mainly used for processed food in these regions, so the requirements for the appearance and quality of garlic are relatively relaxed, and garlic planting agronomy does not particularly emphasize the control of bulb orientation. The efficiency and reliability of mechanization is the primary concern, with relatively low emphasis on indicators such as unit yield and quality. In the field of garlic seeding machinery production, Europe and the United States have a number of well-known companies, such as Spain's Pochi J.J. Broch, France's ERME, the Netherlands' WIFO, and Poland's Garmach[18-21]. A series of garlic seeding machinery has been developed, which has high efficiency, good stability, and good dynamic adaptability, and has achieved large-scale promotion and application in their respective countries. Because of the application of the equipment, Europe and the United States and other countries have achieved a high degree of scale and mechanization in the field of garlic cultivation. However, most of these devices do not have the function of garlic seed scale bud orientation, so they do not meet the agronomic requirements and are rarely used in China.

The PLMS series of garlic seeders manufactured by J.J. Broch, Spain are shown in Figure 3. The seeder focuses on efficient seeding and can adapt to different levels of garlic seeding needs. The plant spacing, which is easy to operate and highly efficient, can be adjusted according to specific needs. Moreover, the machine integrates several sowing steps such as furrowing, seed pickup, dividing, planting, and mulching, greatly simplifying the planting process of garlic. The operator can choose the number of one-time sowing rows (three/four/five/15 rows) according to the actual needs. The minimum row spacing of the seeder is 350 mm, the maximum row spacing depends on the beam length, and these can be customized according to user needs. The plant spacing range is 62.5-142 mm, and the rated sowing speed is 2.5 km/h. The seeder can achieve single seeding, and can also adjust the plant distance and soil depth to sow different size levels of garlic seeds. It has the advantages of strong adaptability, high flexibility, fast seeding speed, and so on. However, the seeder cannot control the orientation of garlic scale buds after planting, and the price of the seeding machine is expensive, thus it does not meet the agronomic requirements of China.

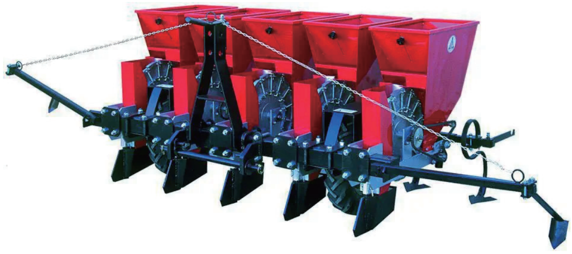

Figure 3 J.J. Broch PLMS garlic planters

As shown in Figure 4, the AGP-8R garlic planter designed by Garmach is a simple and versatile agricultural machine, which is particularly suitable for garlic and onion planting operations in high-quality soil conditions. The minimum row spacing of the machine is 150 mm, and it can be equipped with a variety of chain diameters (22 mm, 28 mm, 36 mm) according to different planting needs. It can also remove part of the planting row, which has a high degree of flexibility in practical applications. The AGP-8R model can be adjusted to a maximum planting depth of 160 mm and a maximum working width of 1050 mm, which is enough for efficient and accurate planting of a variety of tubers such as scallions, garlic, broad beans, and saffron. In terms of technical parameters, the planter requires the power provided by the tractor to be 28 kW, and the machine size to be 2000 mm×1650 mm×950 mm, and the weight of the equipment to be 300 kg. The row spacing is fixed at 150 mm, the seed spacing is adjustable between 90 and 200 mm, and the equipment has good adaptability. In addition, the productivity of AGP-8R is up to 0.2 hm^2/h, which significantly improves the planting efficiency, but does not have the function of adjusting the scale bud direction.

Figure 4 AGP-8R garlic planter

Figure 5 shows a garlic planter produced by the French company ERME, whose garlic planting machinery is highly efficient and has a significant share in the international market. ERME's garlic seeders are available in both mechanical and air-suction methods, which can be selected according to different agricultural needs. The number of sowing rows of the machine varies from three to 15 rows, all of which are traction walking and have good mobility and adaptability. The row spacing is adjustable between 393.7 and 495.3 mm, and the plant spacing is adjustable between 30 and 70 mm, providing great flexibility for different planting patterns. The working speed of the machine is 2.2-3.5 km/h, which can adapt to various working environments. Significantly, the vibration tank of the machine is used to control orientation of the garlic seed scale buds, but the adjustment structure is too complicated to correct the garlic seeds, so the garlic cannot be guaranteed to fall upright into the soil. Therefore, the company's various models still do not have the function of scale bud orientation adjustment, and the recognition and utilization rate of domestic growers is low.

Figure 5 ERME garlic planter

3.2 Status of research on garlic seeder equipment in the Asian region

Asia is an important production area of garlic, and the region has a large cultivated area, but most of it belongs to mountainous and hilly terrain. Therefore, the region needs small and medium-sized garlic seeding machinery that can adapt to the complex terrain of mountains, hills, and plateaus[22]. In recent years, countries such as Japan, Korea, and India have also been actively conducting research related to garlic seeding machines. The more successful ones are HADA Company in Korea and YANMAR Company in Japan, which have developed products that mainly use small row spacing and high-density upright sowing methods, which are especially suitable for mountainous and hilly areas.

The PH4R-GHA self-propelled garlic planter produced by Japan's YANMAR company, shown in Figure 6, is an agricultural machine designed for complex terrain. The machine can directly drill holes on the mulch film to achieve an efficient four-row seeding function, and its operation efficiency is three to four times that of traditional artificial seeding. In addition, the machine is equipped with an automatic navigation system and automatic planting depth control system to ensure the straightness and depth consistency of the sowing operation. However, the effect of the planter in garlic bud active orientation is not good, and two workers are needed to cooperate in garlic planting. Workers are mainly responsible for placing the garlic seeds and ensuring the accurate orientation of the scale buds, which increases labor costs to a certain extent. In terms of equipment parameters, the line spacing of the PH4R-GHA is fixed at 250 mm, the plant spacing can be adjusted between 150 and 170 mm, and the planting depth can be adjusted within the range of 70 to 90 mm. The above design can meet different agronomic requirements. Although the PH4R-GHA self-propelled garlic seeder has significant advantages in technology, it still faces challenges in the process of popularization and application. In particular, the incompatibility with the current domestic agronomic requirements limits its acceptance in specific areas. Although the model has a certain bud orientation adjustment function, the size is moderate, and it is easy to operate, its dependence on manual assistance, high acquisition, operating costs, and efficiency limitations has limited its promotion and large-scale application. Overall, YANMAR's PH4R-GHA self-contained garlic seeder has shown obvious advantages in improving seeding efficiency and quality, but it has a big disadvantage in efficiency and cost of use.

Figure 7 shows the JK-GPS7T garlic seeder manufactured by HADA in Korea, which can seed garlic on soil covered with mulch film. It adopts precise spot seeding technology, which has high efficiency and good operation effect. The seeder can be adapted to the power source alone, but also can be used with small and medium-sized agricultural tractors. It has a simple structure and is conducive to scale promotion. The JK-GPS7T garlic seeder is available in different models with seven, nine, and 11 rows to meet the needs of different planting scales. The fixed row spacing of the machine is 140 mm, the plant spacing is adjustable in the range of 130-180 mm, and the planting depth is adjusted between 0 and 70 mm. The salient feature of the JK-GPS7T garlic seeder is the ability to quickly adjust the orientation of garlic buds. However, this function is mainly achieved by squeezing the prominent scale buds of garlic, which is better for positive buds such as Cangshan garlic, but not suitable for Jinxiang garlic, whose shape is extremely irregular. In addition, the HD-1500 manual semi-automatic garlic seeder (Figure 8) produced by Yongdong Company of South Korea is well-received by the market because of its simple structure, adjustable plant distance, and convenient operation, but it also does not have the function of adjusting the scale bud direction.

Figure 6 PH4R-GHA planter

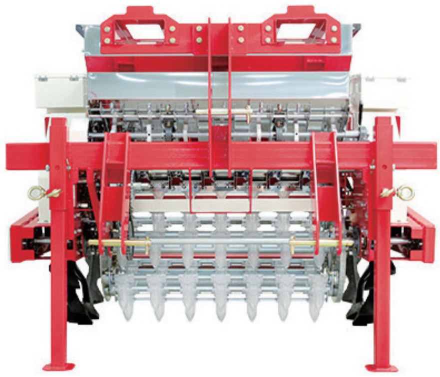

Figure 7 HADA planter

Figure 8 HD-1500 garlic seeder

4 Research on garlic planter equipment and key technology in China

4.1 Domestic garlic seeder development history

"Late start, fast development" is the development characteristic of China's garlic planters. However, after years of unremitting efforts and technological innovation, China has made a series of breakthroughs in the field of mechanized garlic sowing. Figure 9a shows the 2ZDS-5 planter developed by the China Agricultural Machinery Institute[23], which realizes the functions of automatic seed pickup and upright planting for garlic, fills the gaps of domestic garlic seeding equipment, and provides valuable technical references for the industry. As shown in Figure 9b, the box seeder developed by Shandong Agricultural University adopts the seed box seeding. Before seeding, the garlic seeds should be manually put into the seed box in the "bulb up" state, and then the seeder will sow the seed box, which is made of biodegradable materials, into the seed furrow[24]. This method is easy to operate and has a good seeding effect, but it increases the planting cost and the per capita work efficiency is not high. As shown in Figure 9c, the 2BUX-11 garlic planter[25] developed by Shandong Maria Agricultural Machinery Co., Ltd. in cooperation with Shandong Agricultural Machinery Scientific Research Institute, can complete single-seed picking, bulb orientation, upright soil entry, and mulching compaction in one go. This model realizes integrated operation and improves the uniformity and survival rate of planting, but when applied to garlic such as Jinxiang garlic whose bulb buds are not obvious, the effect of bulb bud orientation is average. In Figure 9d, the fourth generation garlic seeder produced by DeYiBo Machinery Development Co., Ltd., is compact, easy to operate, and inexpensive, which is very suitable for small-scale growers. The disadvantages are that the operating efficiency is low and it does not have the function of bulb orientation[22].

a. 2ZDS-5 garlic seeder b. Garlic seed box seeder

c. Maria 2BUX-11 garlic seeder d. DB-DS-5 garlic seeder

e. 2BSZ-12 garlic planter f. 2CS-14 garlic planter

Figure 9 Typical domestic garlic planters

Figure 9e shows the 2BSZ-12 self-propelled garlic seeder jointly developed by Shandong Agricultural University and Linyi Jianling Mould Machinery Co., Ltd. The seeder has rotary tillage and leveling function, rated power 25.8 kW, working width 2500 mm, working row number 12, row spacing 200 mm, plant spacing 100 mm, and planting depth adjustable between 20-50 mm. The chain claw method is used to take garlic seeds, and the spiral spring and bud interaction method is used to adjust the orientation of garlic buds. The field experiment showed that the qualified rate of Cangshan garlic seed bud adjustment was more than 92%, but its seed bud adjustment device was more dependent on the appearance of garlic seed, and had poor effect on Jinxiang garlic seed bud orientation. Besides, Figure 9f shows the air-suction type garlic planter produced by Jinan Zhongyi Machinery Co., Ltd. It adopts the air-suction device for single-seed extraction and uses a spiral spring to adjust the orientation of seed buds. The number of working rows is 14, the row spacing is 180 mm, the plant spacing is 120 mm, and the planting depth is adjustable between 40-60 mm. Working efficiency is 0.2-0.3 hm^2/h.

Through analysis and research, it can be seen that the existing seeding machinery on the market has made important progress in a number of areas such as seed extraction, soil entry, and mulching compaction, but there are still some technical difficulties in the field of bulb orientation. Most of the existing seeding machinery does not have the function of bulb orientation, or is only applicable to garlic seeds with obvious bulb characteristics. Therefore, in order to meet the agronomic requirements of garlic planting in China, research on bulb bud precise orientation device is of great significance.

4.2 Agronomic requirements and key technology for garlic seeding in China

Mechanized seeding of garlic is the inevitable trend of high-quality development for the garlic industry. However, the existing garlic sowing machines have a low qualification rate of single-grain seeding, a low qualification rate and poor adaptability of garlic clove orientation adjustment, and low uprightness in directional sowing. Garlic is a large and medium-sized seed, and the planting agronomic requirements of garlic in China are single-seed planting and directional planting. Reseeding or missing sowing of the garlic will lead to serious yield reduction, and directional planting has the characteristics of neat emergence, early emergence, strong garlic seedlings, and so on, and it is conductive to improving garlic yield and quality.

Insertion of garlic seeds with bulbs facing upwards can lead to earlier and neater emergence of garlic, thicker pseudostem (i. e. bulb) growth, and taller plants, which can significantly improve the yield and quality of garlic[26-28]. As shown in Figures 10 and 11, the bulb-side-up sowing method is significantly better than the bulb-side-down and horizontal sowing methods during the whole growth cycle of garlic. When garlic seeds were sown with the bulb side up, the plants matured with a larger horizontal diameter of garlic head and significantly higher yield per unit area. In addition, sowing garlic seeds with the bulb side up also significantly accelerates germination and improves the consistency of germination, which facilitates mechanized management at a later stage[29-33]. Existing machinery is unable to solve the problem of accurate orientation of garlic seeds with fuzzy bulb characteristics, which seriously affects the mechanization process of garlic planting in China. In order to improve the planting efficiency and garlic quality, it is urgent to develop a mechanical device that can accurately realize the orientation of garlic bulb buds.

Based on the above agronomic requirements of garlic planting, three key techniques of mechanized garlic seeding are summarized in this paper.

(1) Garlic single-seed taking

Garlic generally has large particles with irregular shape and rough indication, which could cause problems such as particle accumulation and arch blockage, resulting in a high leakage rate. Based on this, the single-seed filling device is divided into three types: mechanical type, pneumatic type, and vibration type. Among them, mechanical seed filling occupies the dominant position because of its simple structure, convenient operation, and low cost. Mechanical seed filling includes a variety of extraction methods such as socket-roller type, scoop-chain type, finger-clamping pattern, and scoop-belt type[30,31]. The typical garlic single-seed filling devices are shown in Figure 10.

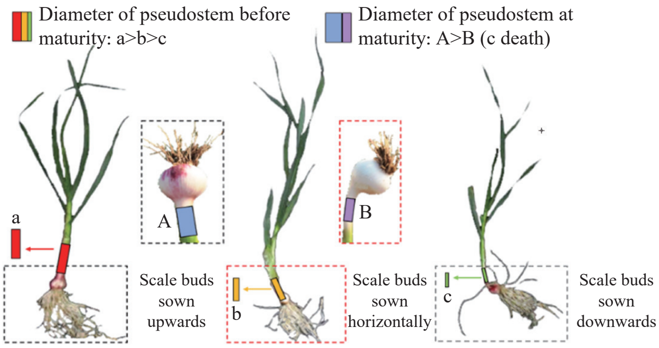

Figure 10 Effect of different scale bud orientation planting methods on plant shape

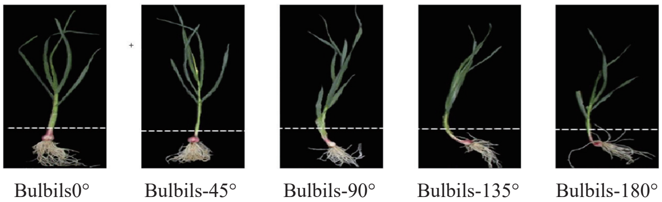

Figure 11 Garlic growth under different states

a) Socket-roller type seed filling is a method adopted in early research in the United States, which was widely used in garlic planters earlier in the century[34,35]. The garlic seeds were extracted from the seed box by the eye-hole wheel, and the garlic seeds fell into the eye-hole device by their own gravity. The device is simple in structure and easy to implement. However, in practice, due to the irregular shape of the garlic seed, the garlic seed in the socket eye may show a variety of poses, which easily causes forced interference between the surrounding garlic seeds and the device in the process of seeding, and may cause damage to the garlic seeds in serious cases.

b) The finger-clamping pattern is widely used in the planting field, especially in the sowing of large seed crops[36-40]. The device consists of a seed bowl and a movable cover plate with a retractable spring at the other end of the cover plate. When the seed bowl is rotated to the position where the garlic seeds are collected, the cover opens so that the seed bowl can collect the garlic seeds. Then the planting bowl drives the garlic seeds out, and the cover is closed, thus ensuring that the garlic seeds will not fall off during the transportation process. When the sorting device is reached, the cover opens again to release the garlic seeds for further processing. The accuracy of the finger clip seed extractor is higher, but when dealing with large size differences in garlic seeds, there is a need to replace different specifications of the seed bowl, which increases the complexity of the operation.

c) In recent years, the scoop-belt and scoop-chain seed filling devices have been widely used in garlic seeding machinery because of their stable working and easy manufacturing characteristics. Both of them extract garlic seed from the seed-taking box by driving the scoop type seed-taking device or sprocket. The working mode of "take more seed first, then clear seed" is often adopted in the seed-taking process, which greatly reduces the leakage rate of the device. In recent years, with the development of technology, the scoop-belt and scoop-chain seed filling structures have undergone a variety of improvements, and have now developed into mature solutions in single-seed collection technology, as shown in Figure 12.

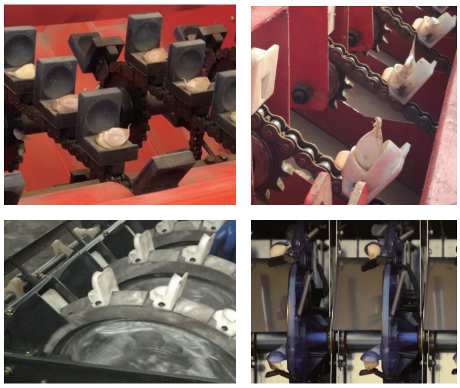

Figure 12 Typical single-seed seeding device

d) Vibrating seed filling mainly uses a vibrating device to vibrate the garlic seed box, aiming to make the single garlic cloves go through the seeding tube successively to complete single-seed filling, as shown in Figure 13. At present, this method has been changed to mechanical CAM mechanism vibration seed collection by South Korea LEE and KIL MI.

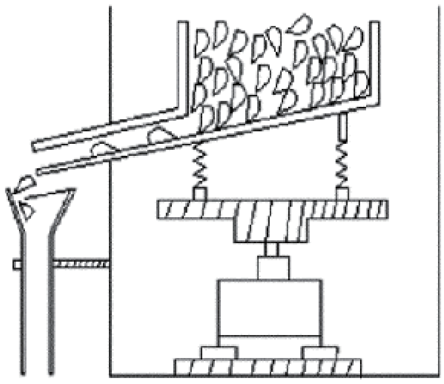

Figure 13 Diagram of vibration type seed filling

e) Pneumatic seed filling is to adsorb and blow garlic seeds by air flow. This method is becoming more and more popular because of its low rigidity and low damage to garlic seeds. Taking PLP3 series air-sucking garlic planter of ERME Company in France as an example (Figure 14), when the seeding device is working, the high-speed fan produces negative pressure, and the seeding disc absorbs garlic seeds under the negative pressure, and rotates with the seeding disc. When leaving the negative pressure chamber, the garlic seeds fall to complete the seeding, and there is no garlic seed tip orientation device. The main advantages of the device are seed saving, small damage to garlic seeds, strong adaptability to the size of garlic seeds, and accurate sowing.

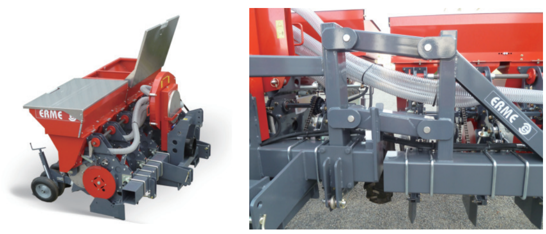

Figure 14 ERME pneumatical garlic planter

(2) Adjustment of garlic seed bud orientation

The identification and automatic adjustment of garlic seed bud orientation is one of the key technologies of the garlic planter. In recent years, many scholars have made attempts and experiments on the adjustment of seed bud orientation. At present, there are mainly two ways for orientation of garlic buds: mechanical type and machine vision-based. Common types of directional devices are rotary funnel type, vibration type, and conduit type: 1) The working principle of the rotating funnel orientation device is that when the garlic bud tip falls down into the garlic hopper with a gap at the bottom, the bud tip will extend out the gap, and the planting device pushes the garlic hopper to open and clips the bud tip to make the garlic seed turn over and fall into the planting device. 2) The working principle of the vibrating directional device is that the garlic seeds pass through the outlet which only allows one grain of garlic seed to pass in the length direction with the vibration of the seed box. Then under the action of the garlic seed orientation baffle, the garlic seeds contact with the bud tips to adjust the orientation; otherwise, the seed passes smoothly. 3) Catheter-type orientation device uses a catheter to connect the seed dispenser and the furrow opener to adjust the correct seed bud orientation in the catheter.

In addition, the common positioning devices in China are three-level directional bucket type, spiral spring type, and water float type, as shown in Figure 15. 1) In the three-level directional bucket directional device, the taper of each layer of the device increases successively. The orientation adjustment state can be divided into two types. One is that the gravity center of the garlic species with the funnel opening moves down during the falling process. The other is similar to the rotating funnel orientation device, in which the attitude of the garlic bud changes through the contact with the funnel during the falling process. 2) In the spiral spring orientation device, when the garlic seed passes through the helical spring seed guide tube, the garlic seed and the bud tip complete the orientation under the action of the friction of the seed guide tube. 3) In the water floating orientation device, when the garlic seed falls into the funnel, water is injected. Then, under the action of buoyancy, the root of the garlic seed faces downward, the bud tip faces upward, and the water slowly drains to complete the orientation.

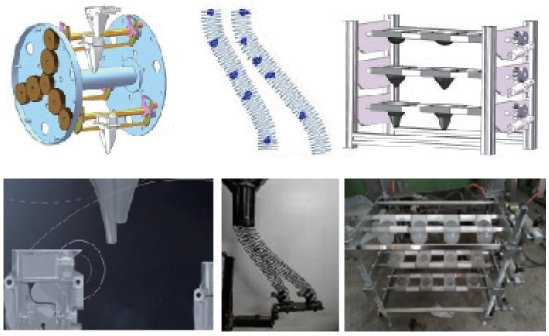

Figure 15 Mechanical clove orientation device

(3) Garlic directional insertion technology

"Upright insertion" of garlic refers to the process of accurately implanting garlic seeds into the soil after single-seed picking and scale-bud orientation. The agronomic requirements for this precision insertion process are as follows: a) proper spacing of rows, spacing of plants, and their consistency; b) appropriate and consistent depth of implantation; and c) reasonable scale bud orientation range[22]. Existing technologies have been able to meet the relevant agronomic requirements in terms of row spacing, plant spacing, and consistency of implantation depth, but how to ensure that garlic maintains the correct bulb orientation during the implantation process is still a key issue that needs to be thoroughly investigated and solved. To solve this problem, the first thing that needs to be solved is the precise orientation of the garlic scale bud. Research results have shown that the orientation of garlic seed buds has important effects on seedling emergence time, yield, and appearance quality. The best results were obtained when the seed buds were tilted upward and within 45°. The heterogeneity of crop planting depth may lead to delayed emergence, which leads to lower yield. Due to the uneven ground, it is easy to have inconsistent garlic planting depth, and some garlic plants are even planted above the ground surface, resulting in a lack of seedlings. In order to solve the problem of inconsistent depth, most of the existing precision planters use imitation grooving.

Directional insertion technology involves the interaction between soil, soil touching parts, and garlic, and the inherent inhomogeneity, discontinuity, and anisotropy of the soil particle medium make it difficult to analyze the internal mechanism by traditional analysis methods. In recent years, the interaction between garlic, inserter, and soil has been studied with the help of discrete element DEM simulation technology, and the correlation law between garlic upright degree and sowing depth has become one of the current research hotspots.

5 Problems and solutions in mechanized seeding in China

5.1 Technical challenges in garlic cultivation in China

In agricultural production practice, the traditional artificial garlic seeding operation is known for its high labor intensity, high labor density, and long time consumption, which directly leads to the low efficiency of garlic planting and high planting costs, which have long been a major problem for growers. As the current rural labor market is becoming increasingly tight, there is a "difficult to employ, labor shortage" phenomenon in the context of the urgent need to mechanize the transformation of the field of garlic seeding. It is worth noting that the seeding agronomy of garlic is different from that of other crops, and the difficulty lies in the need to follow the agronomic requirement of "bulb up"[27,41,42]. Relevant statistical experiments have shown that the rate of bulb orientation of garlic seeds directly affects the final yield of garlic. Bulb orientation can increase the yield by 10%-20%, as well as the quality of molded garlic and resultant economic benefits[43,44].

5.2 Problems in mechanized seeding in China: A case study of Jinxiang

Jinxiang County, located in Jining City, Shandong Province, enjoys the reputation of "the world's hometown of garlic". Jinxiang garlic has high nutritional value and unique flavor and is widely planted in China, but the cultivation process still relies heavily on manual labor, which is time-consuming, labor-intensive, and costly. The main reason is the unique biological structure of Jinxiang garlic: the bulb buds are short and not protruding, and the texture is soft. Coupled with the unevenness of growth conditions, the bulb buds of garlic species have obvious differences in morphology[27,45,46], and the unique bulb bud structure has brought great difficulties to the orientation of garlic clove buds.

5.3 Bulbil orientation strategies based on mechanical structural innovation

In 2009, a conical spiral conduit structure designed by Shichun Jian and other researchers was used to achieve directional sowing of garlic. The device adopted an innovative spring-guided mechanism that utilized the interaction of the garlic seeds with the spring slits as they fell to achieve the correction of bulb orientation. The design takes into account the physical characteristics of the garlic seeds, and the validity of the design was verified experimentally. However, this device is not suitable for garlic varieties with inconspicuous characteristics[47].

In 2018, Geng et al.[44] used a three-stage conical hopper to realize the orientation of garlic bulb buds, and they designed a three-stage hopper structure with a decreasing half-apex angle to gradually adjust the position of garlic seeds to control bulb bud orientation. In the same year, Hou et al.[41] developed a double duckbill type garlic seeding machine, which realized the accurate orientation of garlic seeds by mechanical extrusion of the bulb buds and gravity when the bulb buds were facing downward.

Further research continued in 2019, when Qin et al.[48] designed a multilayer correction mechanism and combined it with ADAMS software to simulate and verify the motion trajectory, proving that the multilayer correction significantly improved the proportion of garlic seed bulb buds upward. Li et al.[39] used EDEM software to simulate and analyze the influence law of different operating parameters on the performance indices, which further contributed to the research on garlic seeder performance.

In 2023, Cui et al.[49] designed a curved duckbill-type garlic positive sprouting seeder, which could complete seed picking, direction changing, upright planting, and suppression operations in one go. With Cangshan four-six-clove garlic and Jinxiang hybrid garlic as the test objects, the traveling speed was in the range of 0.14-0.19 m/s, the positive sprouting rate of Jinxiang hybrid garlic reached about 85%, and that of Cangshan four-six-clove garlic was about 90%. The rate of single seeding reached more than 93% in both cases, and the overall seeding agronomy requirements of garlic were met.

The design of these studies and devices centers on taking full advantage of the biomorphological properties of garlic, such as its center of gravity near the bottom and the narrow shape of the bulb, to achieve precise adjustment of bulb orientation. These techniques have shown good results for garlic varieties with regular and easily recognizable shapes. However, for garlic varieties with widely varying shapes, irregular center of gravity positions, and short, soft bulbils, the existing techniques are not sufficiently adaptable to meet the agronomic requirements for planting.

5.4 Bulbil orientation strategy based on intelligent control

In recent years, some scholars have introduced methods such as signal processing and image recognition into the field of scale bud orientation and achieved certain research results. This kind of research involves advanced technologies such as computer vision, machine learning, and sensors, and has the advantages of accurate orientation and high success rate.

As shown in Figure 16, Li et al.[50] proposed a multi-featured bulb bud recognition method, which uses an industrial camera to capture images of garlic before it enters the adjusting device, and determines the orientation of garlic by analyzing the image features. The device has a specially designed orientation structure for guiding the garlic in different directions, which helps in the alignment of the bulb buds. In order to improve the accuracy of bulb orientation recognition in images, a multi-feature algorithm was introduced in the study, which has higher accuracy compared to single-feature recognition methods, and is particularly suitable for garlic varieties with ambiguous bulb characteristics.

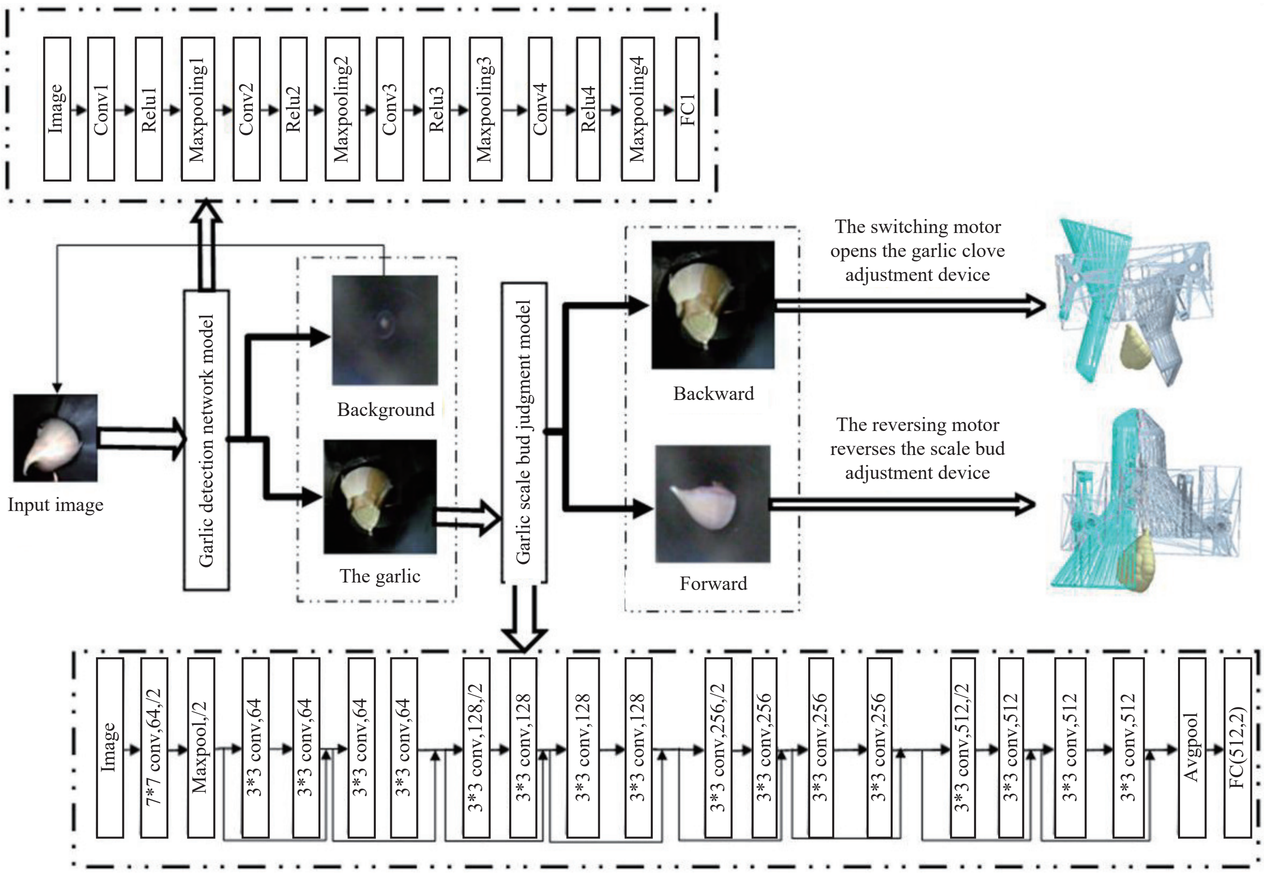

Figure 16 Multi-feature clove recognition method

As shown in Figure 17, Hou et al.[51] proposed a binocular image recognition-based orientation scheme for garlic bulb buds. A single-seed sowing device removes garlic from the planting box, and the garlic is arranged horizontally and descends evenly in the

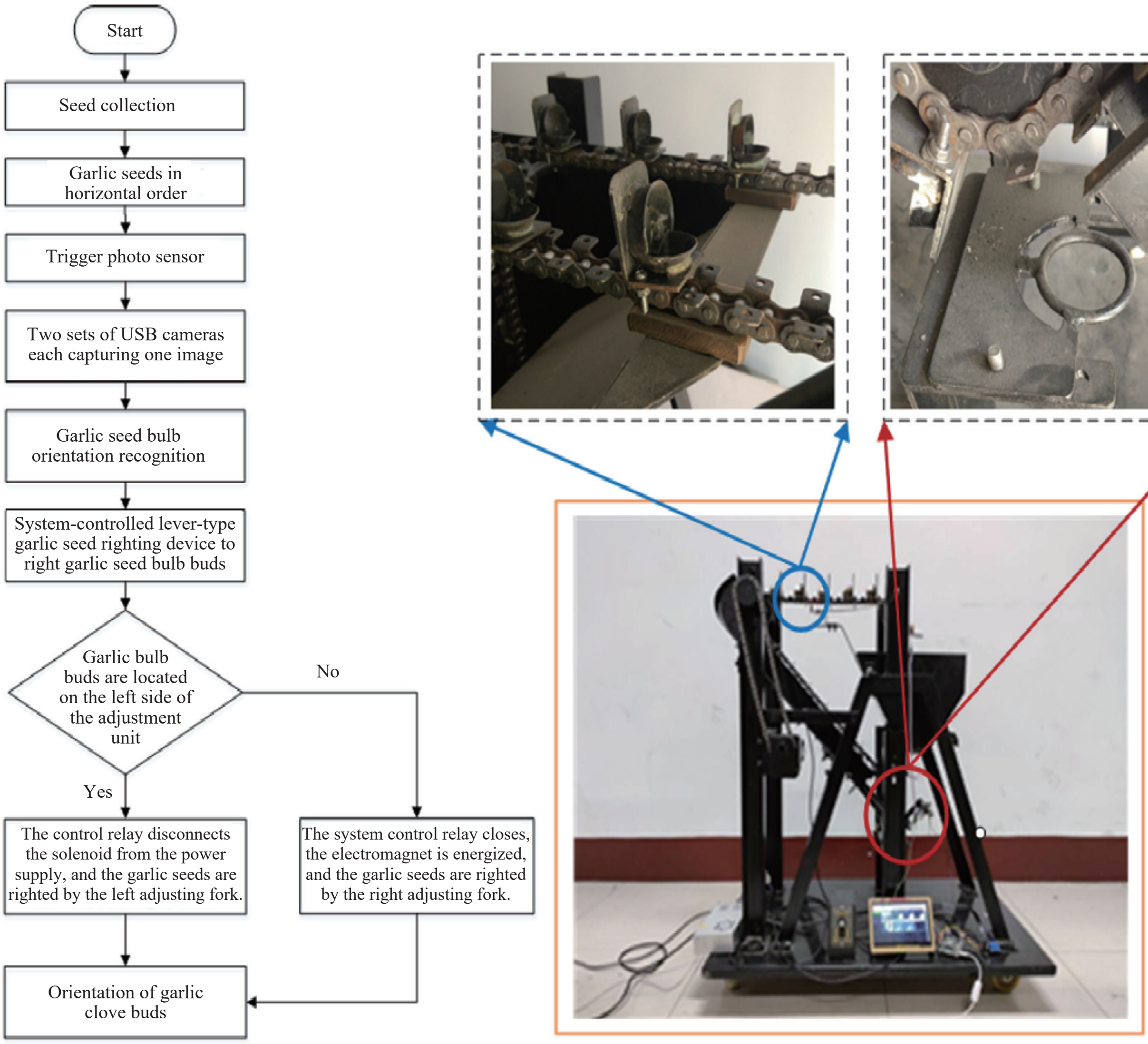

Figure 17 Garlic orientation scheme based on binocular image recognition

channel. When the garlic reaches the image capture point, the U-shaped photodetector is triggered, the USB camera captures the image, and the processor recognizes the bulb orientation and controls the lever-type bulb correction mechanism. As shown in Figure 18, Geng et al.[44] designed a garlic orientation device using infrared sensing detection based on the unique bulb end structure of garlic with partially open grooves at the bottom of the funnel. The grooves allow inverted bulb buds to probe out, and the infrared sensors determine the orientation of garlic clove buds by detecting the presence of bulb buds.

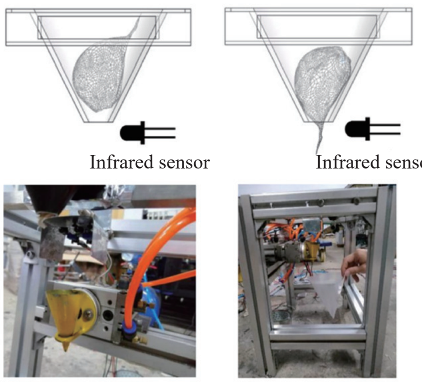

Figure 18 Garlic orientation device using infrared sensors

In 2022, Li et al.[40] designed a garlic leakage detection and reseeding device with laser sensor, rotating spoon reseeding device, and reseeding box as the core, and built a test bench for the problem of leakage in the process of seed taking by spoon-chain garlic seeder. It effectively solved the problems of leakage and overtaking in the sowing process, laying a foundation for realizing the accurate orientation of scale buds.

In 2023, Hou et al.[46] proposed a method of orientation of garlic clove buds based on capacitance detection technology, built a corresponding bulb detection and righting device, and optimized its structure and operating parameters. With Jinxiang and Cangshan garlic seeds as the test objects, the prototype test was carried out, and the positive bud rate was 95.0%, which met the requirements of garlic sowing. As shown in Figure 19, in 2024, Fang et al.[52] proposed a fast orientation of garlic clove buds based on capacitance sensing, which utilizes the characteristic differences in capacitance changes associated with different orientations of clove buds to determine the state of garlic clove buds. Li et al.[53] designed a plant-correcting reel for harvesting lodging garlic plants to solve the problem of lodging garlic plants. There is no standardized row spacing for garlic planting across different regions of China. However, row spacing typically ranged between 180-220 mm. The agronomic requirements of garlic sowing should be also considered in design of garlic seeding machine.

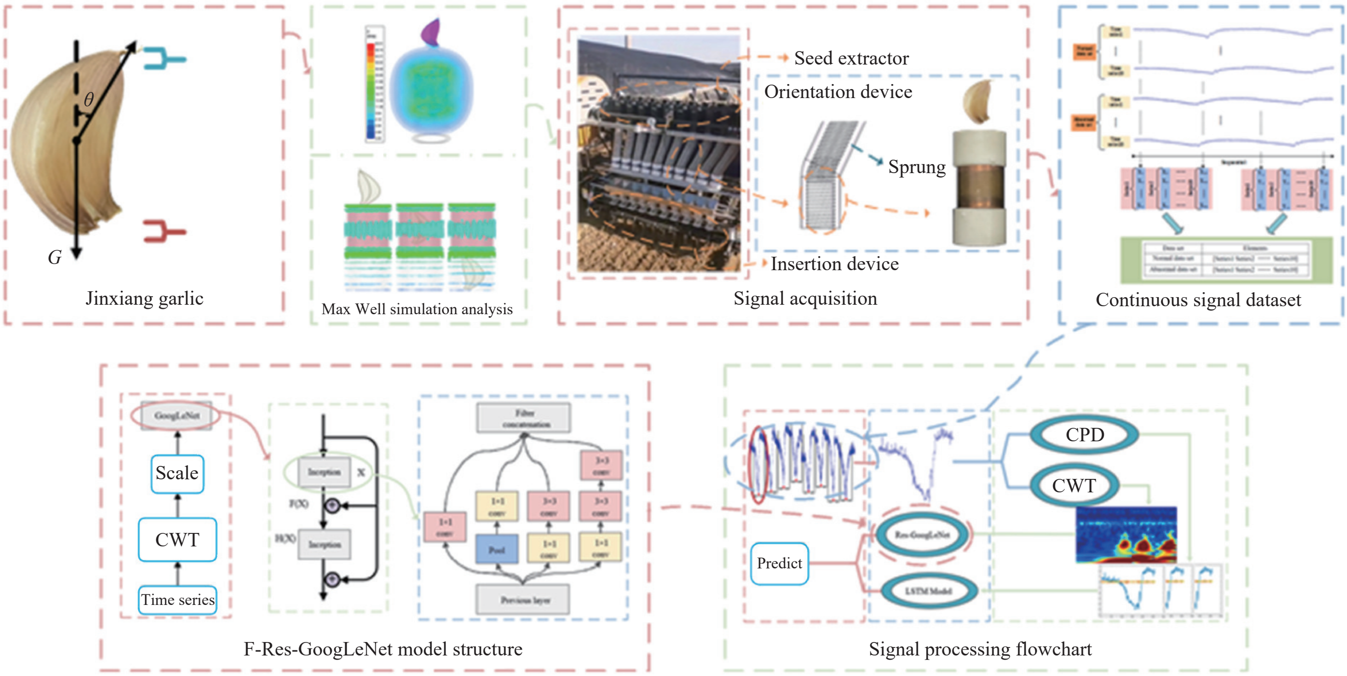

Figure 19 Garlic orientation scheme based on capacitance sensing

6 Conclusions

Garlic production and consumption in China perennially ranks first in the world, but with the continuous development of the society and economy in recent years, fertilizers, pesticides, and other planting costs have increased, as well as labor costs in general, which has led directly to the climbing of the total cost of garlic planting year after year. Affected by this, garlic planting profits have declined, and planting area continues to decrease. In order to consolidate China's dominant position in the field of garlic planting, mechanization has become the road to future development.

In the field of mechanized planting of garlic, Europe, the United States, and other Western developed countries have a high level of mechanization, but most of them do not have a bulb orientation function, and therefore cannot meet the agronomic requirements of China. In recent years, South Korea, Japan, and other countries have developed a variety of garlic seeding machines with a bulb orientation function. However, the difficulty of acquiring this kind of machinery, its high cost of use, and the fact that these machines are geared toward a fixed type of garlic render them unable to solve the problem of the orientation of garlic seeds with fuzzy bulb characteristics.

In recent years, China has conducted a series of research projects in the field of mechanized sowing of garlic and achieved many results. The innovative method based on mechanical mechanisms shows high efficiency and accuracy when dealing with garlic seeds with regular shape. However, when it comes to garlic seeds with ambiguous clove bud characteristics and obvious inhomogeneity of biological morphology, the effectiveness of achieving the orientation of garlic clove buds through mechanical mechanisms is significantly reduced. To address this challenge, computer vision and infrared technologies have been introduced to enhance the orientation of garlic seeds with ambiguous bulb characteristics. However, these state-of-the-art technologies still face multiple challenges in practice, such as mechanical vibrations and object obstructions that often interfere with the image acquisition process, thus seriously affecting the recognition accuracy. Thus, despite some advances in the field of bulb orientation, current technical solutions are still not effective in solving the problem of accurate orientation of garlic seeds with fuzzy bulb characteristics.

In the future, China needs to focus research on the precision orientation of garlic seeds with fuzzy bulb characteristics. The most effective breakthrough direction is machine vision and intelligent sensing, whose focus is how to effectively collect operating signals, reduce interference, and improve recognition accuracy. When conducting research, it is necessary to comprehensively consider the complex working environment of agricultural machinery and field operations, and the research method needs to have strong anti-interference ability and work stability. In addition, it is also necessary to consider the manufacturing cost of the device and the cost of use, and comprehensively design the actual situation of agricultural machinery.

In addition, it is also necessary to demonstrate and promote mechanized garlic planting. For example, demonstration bases should be established in the main producing areas to promote advanced garlic seeding machinery and technology through on-site demonstrations and technical training, so that more growers could understand and accept mechanized seeding. Keeping up with the market demand, garlic seeding machinery suitable for the needs of different regions and growers of different sizes should be developed. A platform can be built to promote the integration and innovation of advanced garlic production equipment and technology. Through the integration of technology, a set of mechanized solutions suitable for China's garlic production will eventually be formed, further enhancing the technical level of the entire industrial chain.

Acknowledgements

This work was financially supported by National Key Research and Development Program (Grant No. 2022YFD1602400), the Central Government for Guiding Local Science and Technology Development (No. 2024ZY044), and the Key Laboratory Project of Qinghai Science & Technology Department (Grant No. 2023-1_4).

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