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Research Progress and Prospects of Mechanical Weeding Devices and Technologies

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Abstract

Repeated, high-dose herbicide applications have bred resistance in weed populations and raised concerns over environmental contamination and food safety, which makes mechanical weeding an attractive alternative for reducing chemical inputs without sacrificing weed control. This review follows a single thread: how weeding tools and sensing have converged. Passive tools are examined first, including counter-rotating finger discs, spring tines and finger wheels. Active intra-row devices that avoid crop plants follow-vertical rotary units, synchronized inter-/intra-row machines, pendulum types and tactile-vibratory designs. Combined mechanical units and non-contact options such as water jets and lasers are then compared with single-mechanism mechanical devices in working principle, sensing requirements and field performance. Machine-level progress is summarized for four production settings: paddy fields, upland fields, orchards and open-field vegetables. On this basis four problems are analyzed: the low intra-row weeding rate coupled with a high crop injury rate; unstable perception in complex field environments; poor machine versatility and weak fit with local agronomy; and an incomplete validation system together with limited commercialization. Four directions are proposed accordingly: fusing structural adaptivity with sensor-guided avoidance, deploying multi-sensor fusion and lightweight edge models, integrating mechanical weeding with reduced herbicide doses, and standardizing machine-friendly agronomic practice. The aim is to inform equipment development, standard setting and the implementation of policies that reduce herbicide use in China.

Keywords

Mechanical Weeding; Weeding Device; Intra-Row Weeding; Crop-Plant Avoidance; Machine Vision; Herbicide Reduction

1. Introduction

Weeds have been a persistent burden on Chinese farmland: they are species-rich, widely distributed and dense, and they cause losses of about 60 million tons of grain each year, a loss worth some CNY 220 billion[1]. Worldwide, Oerke ranked weeds

first among pest groups, with a potential yield loss of about 34%. Maize suffers more, with a potential loss of 40.3% and an actual loss near 10.5% even when control measures are applied[2]. Chinese figures tell a similar story. Grass weeds cut maize yields by more than 10% in ordinary years and by up to 20% in severe outbreaks[3], while soybean loses both yield and quality when weeds compete for light, water and nutrients[4]. Chemical control still accounts for most weed control; in rice, herbicides are applied on more than 90% of the planted area. Applications are frequent and doses are high, and resistance has followed. Ecosystems and food safety are under pressure as well[5]. The survey by Heap et al. makes the point: by 2017, 38 weed species in 37 countries had evolved resistance to glyphosate, and no herbicide with a new mode of action had reached the market for more than three decades, which casts doubt on how long chemical programs can be sustained[6]. Mechanical weeding has therefore drawn renewed interest. Besides killing weeds, the tools stir the soil and raise its oxygen content, which favors nutrient uptake, and the practice is regarded as environmentally sound[5]. Field trials by Luo Ziqiang and co-workers offer more direct support: mechanical weeding lowered pesticide residues in the soil appreciably, which fits the policy goal of cutting herbicide use while maintaining efficacy[7].

Historically, the technical route has moved from purely mechanical practice supported by agronomy towards a perceive-decide-act loop. In the 1950s the emphasis was agronomic: early spring tillage was used to stimulate weed emergence, pre-sowing harrowing removed the flush, and mechanical weeding followed at the seedling stage[8]. As late as 2006, Chinese inter-row cultivators still relied mainly on single and double-wing sweeps, whereas American and Japanese manufacturers already offered roller, disc and flail configurations as a fairly complete family of machines[9]. After 2019, machine vision, deep learning and automatic control entered the field on a large scale[10][12], and in recent years crop-row detection, avoidance control and multi-sensor fusion have been listed together as the three key links of an intelligent weeder[13]. Efficacy and work rate still lag behind chemical control, and most intelligent machines remain prototypes tested in plots.

Field conditions impose a second constraint. In machine-transplanted rice the row spacing is fixed at 250-300 mm and the intra-row spacing is only 10-17 cm, so the intra-row space is narrow and seedlings grow mixed with weeds; the shallow water layer adds reflections and a shifting mud background that disturb vision[14]. On ridge-tilled upland the ridge surface undulates by 30-80 mm, residues cover the soil under flat planting, and seedling roots are shallow and stems tender[3]. Soils in Xinjiang are compacted and highly cohesive, which makes penetration difficult for conventional tools[15]. Orchards vary widely in planting pattern, are not well adapted to mechanization, and leave little room under the canopy[16]. Open-field vegetables are densely planted with narrow rows and demand the highest

accuracy[17]. Such diversity means that no universal machine exists, and it is also why this review organizes the literature by device type and enabling technology. Only three levels are covered: weeding tools, sensing-based avoidance, and complete machines for different settings. Agronomic measures such as stale seedbed preparation and mulching are outside the scope. The paper first surveys the state of the art, then analyzes the problems and proposes directions for equipment research and design.

2. Current status of mechanical weeding devices

Mechanical weeders fall into two broad groups, depending on whether crop position information is used. Passive tools exploit differences in crop-weed morphology, root systems and soil resistance; they need no positioning and work fast, but their weeding rate is modest. Active, or selective, tools act on crop position and depend on the accuracy of detection and localization; they weed better but more slowly. The most interesting recent development is the convergence of the two routes.

2.1. Passive weeding tools

Passive tools include three main forms: counter-rotating, spring-tine and finger-wheel. A counter-rotating unit (0) consists of a pair of oppositely driven rubber finger discs, brushes or spring-tine wheels that uproot and bury weeds, with working depth usually held between 10 and 30 mm. Finger-wheel weeders (0) combine rigid and flexible elements: a rigid finger disc and a flexible rubber finger wheel are mounted in pairs at an angle on either side of the crop row, and soil resistance turns them so that weeds are rolled up while seedlings pass unharmed[15]. Tei et al. tested processing spinach in central Italy. At a row spacing of 0.25 m, the German Kress ground-driven finger weeder achieved 64% control, against 90% for flame weeding and 88% for a separate hoe in the same trial; the finger weeder injured no crop plants, but its efficacy was clearly lower[18]. The review by van der Weide et al. notes that European work on intra-row weeding over the past decade has centered on spring-tine harrows, torsion-spring and finger weeders and pneumatic devices, and that these are now being combined with advanced sensing on the way to intelligent machines[19].

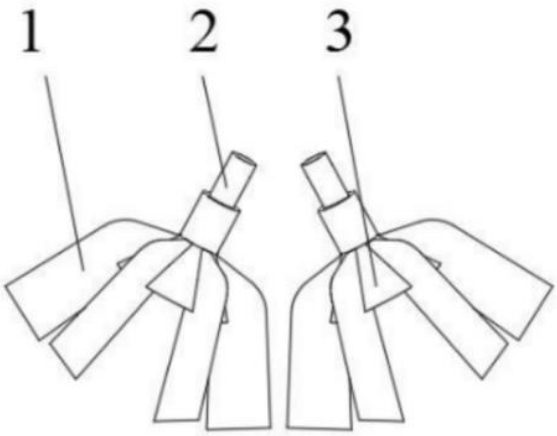


Figure 1. Schematic of a counter-rotating weeding unit

(1 wheel teeth; 2 stepped shaft; 3 disc).

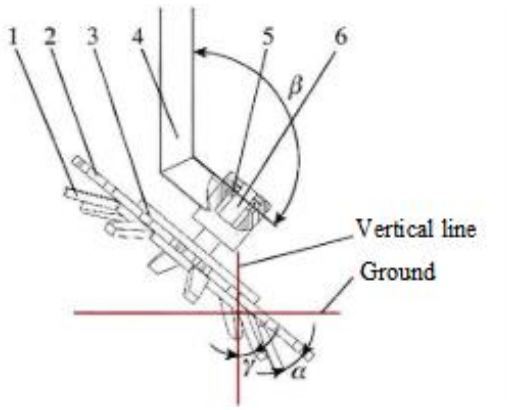
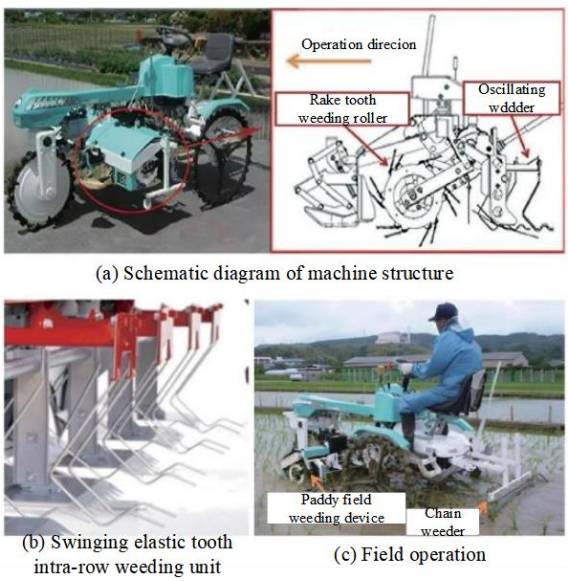


Figure 2. Schematic of a finger-wheel weeder

(1 rigid finger disc; 2 flexible finger wheel; 3 press plate of the finger wheel; 4 bracket; 5 bearing; 6 rotating shaft).

Passive tools have also been studied and commercialized extensively for paddy fields, where conditions happen to suit them. Machine transplanting fixes row spacing at 250-300 mm, which provides a reliable geometric reference: a tool can follow the row without any sensing, and its weakness in the intra-row zone is partly concealed. Japan started early and now has mature synchronized inter-/intra-row machines. In 2007 the national agricultural research organization, together with Iseki and Kubota, developed a high-precision riding-type paddy weeder (0) that used rotary tines between rows and oscillating elastic tines within rows; at 0.4-0.6 m/s it removed more than 85% of inter-row weeds but only about 50% of intra-row weeds[20]. The 2BYS-6 paddy cultivator built by Wu Chongyou et al. (0) follows a similar logic, rotating between rows and swinging within them; in transplanted paddies the mean relative weeding rate between rows was 78.1%, working depth

was 4.39 cm and crop injury stayed below 6.89%[21]. Wang Jinwu et al. took a different starting point and reshaped the teeth themselves, producing an inclined curved-tooth device for inter-row weeding (0). LS-DYNA fluid-structure coupling simulations and orthogonal virtual rotation tests fixed the tooth curvature radius at 66 mm and the eccentricity at 113 mm; field trials gave an average weeding rate of 89.66% with only 2.1% crop injury, and the curved teeth outperformed flat ones both in burying weeds and in shedding soil[22]. A survey of intra-row actuators by Du Jie et al. points the same way: notched-disc, brush, finger and sweep designs differ in form, yet their selectivity still comes mainly from geometry[23]. Long-running European work reaches a similar conclusion. Melander et al. concluded from a systematic review that non-chemical methods such as inter-row hoeing already control weeds well between rows, while intra-row weeds still require substantial hand labor; raising selectivity within the row is the key to non-chemical weeding[24]. Strengths and weaknesses are thus both clear: passive tools are simple and need no sensing, but their intra-row efficacy is generally poor, and in difficult soils or under paddy conditions the weeding rate is hard to guarantee.



(a) Schematic diagram of machine structure

(b) Swinging elastic tooth intra-row weeding unit

(c) Field operation

Figure 3. High-precision riding-type paddy weeder developed in Japan

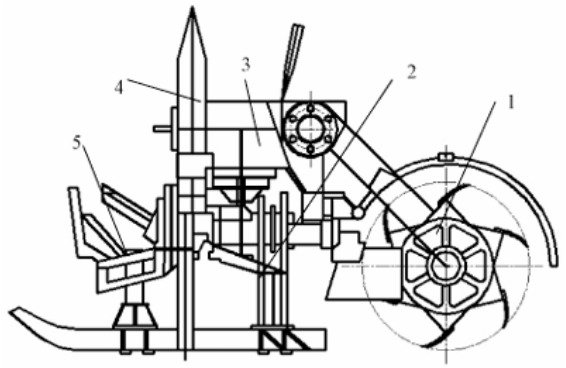


Figure 4. 2BYS-6 paddy inter-row cultivator

(1 inter-row rotary weeding unit; 2 intra-row oscillating weeding unit; 3 power transmission system; 4 frame; 5 hydraulic profiling mechanism).

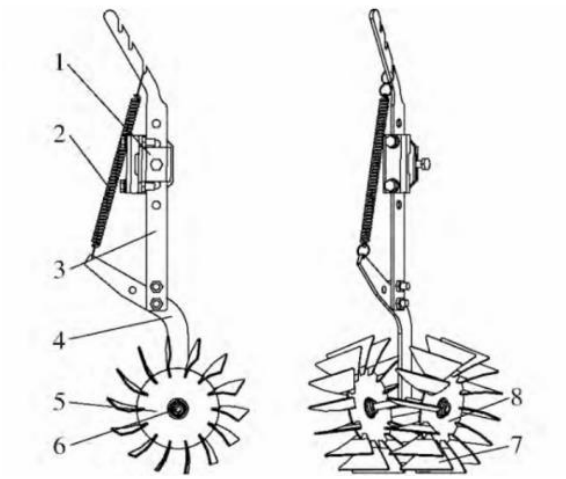


Figure 5. Inclined curved-tooth device for inter-row weeding in paddy fields

(1 mounting frame; 2 pressure-adjusting spring; 3 bracket; 4 weeding-wheel mounting bracket; 5 curved-tooth weeding wheel; 6 fixed bearing; 7 curved weeding-wheel tooth; 8 weeding-wheel disc).

2.2. Active intra-row devices with crop-plant avoidance

Active avoidance devices include vertical rotary, synchronized inter-/intra-row, pendulum and tactile-vibratory types. Their operating logic is the same: crop position obtained by sensors drives the tool to avoid seedlings while weeding. This is where most recent research has concentrated. The four types described below differ in structure and sensing, yet the recognition and navigation techniques behind them are converging quickly on deep learning and multi-sensor fusion, so they are reviewed together.

Vertical rotary type. Most intelligent intra-row weeders use horizontal rotating discs, which cannot easily avoid plants in the space beneath the canopy. Quan

Longzhe et al. developed a vertical rotary unit for maize (0) that exploits the spatial path of a vertical blade to work below the canopy and avoid seedlings. Parameters were fixed by theoretical analysis and EDEM discrete-element simulation; orthogonal tests ranked the factors as forward speed > working depth > blade angle, and the best combination was 0.5 m/s, 50 mm and 60°, giving an average field weeding rate of 89.57% and a crop injury rate of 4.54%[25]. Avoidance below the canopy is achieved, but the speed ceiling is low and high-speed field work is out of reach.

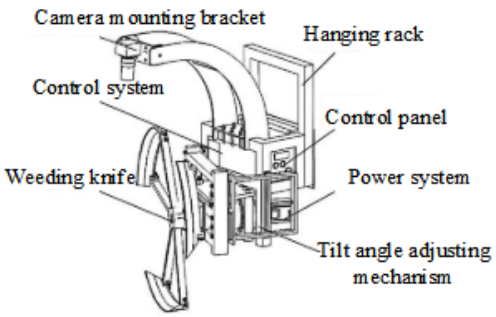


Figure 6. Vertical rotary intelligent intra-row weeding device

Synchronized inter-/intra-row type. Here the efficiency of inter-row work and the delicacy of intra-row avoidance are separated. Inter-row and intra-row units are mounted independently and coordinated by a two-stage profiling mechanism, an arrangement Liu Chuang et al. built into a machine matched to a riding transplanter chassis (0). In field trials, forward speed had a greater effect than weeding-wheel type on both weeding rate and crop injury, and both weeding rate and crop injury first decreased and then increased with increasing speed. An umbrella-shaped wheel performed best overall: at 0.7-1.0 m/s the intra-row weeding rate was 74.6%, the whole-machine rate 83.6% and crop injury 1.6%[26]. The group later completed a wide machine. Based on weed emergence patterns, 13-15 days after transplanting was identified as the optimum control window, and the machine worked the intra-row zone before the inter-row zone. Discrete-element simulation, with soil disturbance area as the index, fixed the geometry of the intra-row wheel. The resulting unit was 1900 mm wide and covered seven working rows, with helical teeth on the outer edge between rows and helical wheels that followed soil undulation within rows; at 0.8 m/s and 70 mm depth it reached 88.34% weeding, 1.67% crop injury and 0.58 ha/h, which was 3.2 percentage points higher in weeding rate and 0.83 percentage points lower in crop injury than the previous model[27]. Wide and efficient, the machine is nevertheless tied to paddy fields and travels poorly elsewhere.

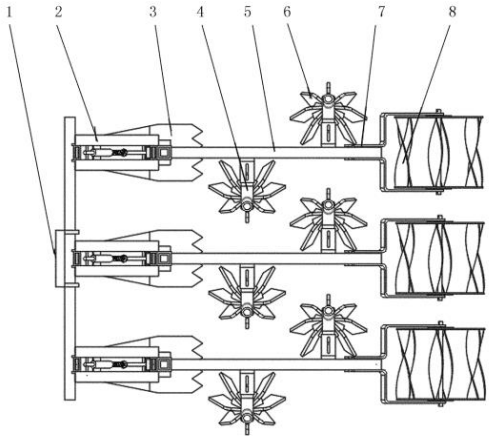


Figure 7. High-efficiency synchronized inter-/intra-row weeding device for paddy fields

(1 hitch device; 2 first-stage profiling four-bar linkage; 3 float plate; 4 bearing sleeve; 5 T-shaped frame; 6 intra-row weeding wheel; 7 second-stage spring profiling mechanism; 8 inter-row weeding wheel).

Pendulum type. Among pendulum machines, Outside China, commercial vision-guided hoes have reached the stage of multi-system field comparison. Kimmel et al. tested six robotic-assisted systems in sugar beet. Robovator and Farming GT, both equipped with selective intra-row hoes, controlled up to 80% of intra-row weeds, better than the 67% obtained with broadcast herbicide, and exceeded 90% between rows; the hoeing pass also buried up to 33% of plants without killing them and uprooted and killed 5.5%[28]. In China, Zhou Fujun et al. built a cam-rocker pendulum unit for maize (0). A Hall-effect proximity sensor detected the plant, and a cam pushed the rocker so that the blade swung back to avoid it. Orthogonal soil-bin tests gave an optimum of 60 N/mm spring stiffness, 0.6 m/s forward speed and 130 r/min blade speed, and validation trials produced 89.8% weeding with 2.1% crop injury[29]. Inertia is the weak point: at high speed the swing response lags, and further optimization is needed.

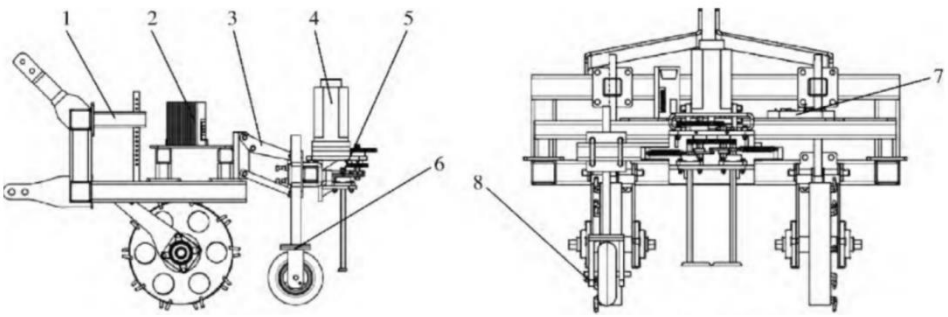


Figure 8. Cam-rocker pendulum intra-row weeding device for maize

(1 frame; 2 motor drive controller; 3 unit profiling device; 4 servo motor; 5 cam-rocker pendulum weeding unit; 6 unit depth-limiting wheel; 7 microcontroller; 8 Hall-effect proximity switch).

Tactile-sensing vibratory type. Intra-row weeding depends heavily on how well a machine follows the row, and Chen Xueshen et al. attacked that dependence directly with a double-row flexible-brush machine (0). The front row combed and pulled weeds. Air-pressure sensors picked up the mechanical response of rice roots and brush fingers as a change in potential, and a lodging-recognition model built on potential kurtosis and mean with a support vector machine reached 83.11% field accuracy. The rear row started and stopped transverse vibration according to that result. In comparative trials, vibration without sensing gave 58.11% weeding and 21.39% crop injury; treatment with neither sensing nor vibration gave 27.89% weeding and 4% crop injury; sensing combined with vibration gave 56.17% weeding and 5.83% crop injury[30]. Tactile sensing cut crop injury to roughly a quarter, at the price of a weeding rate well below that of rigid avoidance. No row-following is required, which makes the approach attractive for small, irregular fields, though the weeding rate still has to rise.

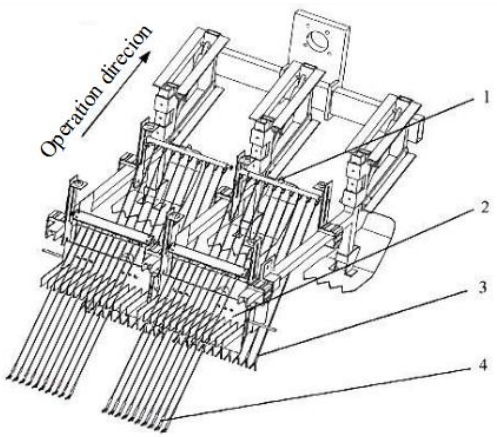


Figure 9. Double-row flexible-brush adaptive vibratory weeder

(1 lodging-recognition system for rice plants; 2 adaptive vibration system; 3 front weeding row; 4 rear weeding row).

Set side by side, these active devices share one difficulty: speed, weeding rate and crop injury constrain one another. Most prototypes perform well in soil bins and small plots, but once speed is raised, avoidance or recognition fails to keep up, injury rises and weeding falls. Each mechanism is also tailored to one crop and one agronomic setting, so a change of crop or field usually means redesign. That is part of the reason these machines remain short of commercialization.

2.3. Combined mechanical units and non-contact weeding approaches

Combined units. When a single mechanism fails in difficult soil, combining several is more effective. For the compacted upland soils of Xinjiang, Liu Jinbao et al. designed a unit consisting of a herringbone sweep, a flexible rubber finger wheel and a rigid finger disc (0), in which deep loosening between rows and shallow weeding within rows are shared by different components. EDEM simulation and

orthogonal tests gave a finger-wheel diameter of 200 mm, a bend angle of 130° for the rigid disc and 16 teeth on the flexible wheel; field results were 82.4% weeding, 2.65% crop injury and 91.87% soil pulverization[15]. The rigid sweep breaks the compacted layer, the flexible wheel cushions the seedling, and loosening and weeding are done in one pass-that is the gain. The cost is more parts and more tuning, rubber fingers that wear and catch weeds, and a speed that is hard to raise.

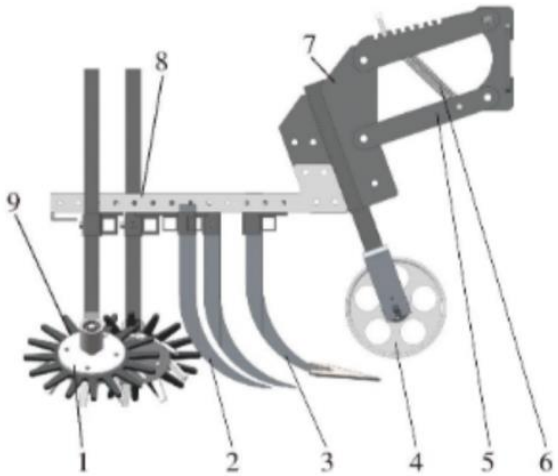


Figure 10. Combined weeding unit

(1 finger-wheel weeding disc; 2 subsoiler; 3 herringbone sweep; 4 profiling wheel; 5 parallel four-bar linkage; 6 profiling spring; 7 suspension device; 8 frame; 9 weeding finger).

Water-jet and laser systems. Non-contact weeding replaces mechanisms with energy and moves the working interface from the soil to the weed itself. For intra-row work in paddies, Wang Ye et al. proposed a water-jet process that strips weed roots by high-speed impact. Simulation and field trials showed that at a jet angle of 45°, a velocity of 6 m/s and a particle diameter of 6 mm, effective soil erosion reached 37.61 mm in depth; the process has so far been shown to be feasible, but field weeding rates have not been reported[31]. Laser weeding has advanced faster and is now verified in the field. Zhao Xueguan et al. combined stereo vision with a parallel manipulator; a HAD-YOLO model performed recognition with a mean average precision (mAP) of 94.2%, the manipulator located targets with a mean relative error of 1.73%, and 90% of laser shots hit the target. Weed mortality was 78% for Amaranthus retroflexes, 72% for Eleusine indica and 82% for Chenopodium album, 77% overall[17]. Wang Wei optimized the structure of a laser weeding robot and reduced body vibration by more than 22% while cutting positioning error by over 25%, to within 0.3 mm[32]. Outside China, commercial validation is under way. Zhu et al. coupled the YOLOX object-detection model with a blue-light laser module in a maize-field robot that recognized and killed weeds while travelling[33]. Sosnoskie et al. ran multi-site trials in vegetable fields in New Jersey and New York in 2024-2025 and found the deep-learning-driven commercial

Laser Weeder (0) equal to or better than conventional herbicides for peas, spinach and beet; weed biomass at the end of the season fell by more than 97% and crop biomass rose by more than 30%[34]. This is the most convincing field evidence for laser weeding so far. Jets and lasers both avoid soil disturbance and direct contact between tool and crop. Equipment cost is high, however, and work rate is generally lower than that of mechanical methods, which keeps both from large-scale adoption.



Figure 11. Commercial laser weeder (Laser Weeder)

2.4. Progress in scenario-specific machines

Paddy fields. Mechanized weeding presupposes standardized row spacing from transplanting or direct seeding; broadcast-sown fields lack regular rows and are unsuited to it. In the trials of Luo Ziqiang et al., pure mechanical weeding under direct seeding gave a weed control efficacy of only 76.67% based on weed dry weight, well below the 98.42% of chemical control, and 88.37% under transplanting. Yield responses differed. Direct-seeded rice yielded most under pure mechanical treatment, 5.29% above chemical control, whereas transplanted rice yielded most under a chemical-mechanical combination, 18.86% higher; mechanical weeding also lowered soil pesticide residues appreciably, with reductions ranging from 74.51% to near-complete removal[7]. In the BeiDou-guided row-following trials of Su Wei et al., weeding rates at 3, 4 and 5 km/h were 88.79%, 85.70% and 83.14%, all meeting the requirements of the local standard DB23/T 930-2005; higher speed meant less weeding and more injury. Chemical control gave a slightly higher yield, but the difference was not significant[35].

Upland fields. Upland is where intelligent machines are used most widely. Foreign products already work continuously for 24 h, recognize weeds with over 98% accuracy and operate three to five times faster than conventional methods; domestic manufacturers have also released intelligent row-following robots with accurate

avoidance and dual vision-BeiDou navigation[3]. A gap in the machine family remains. Domestic intelligent machines, self-propelled machines and trailed machines achieved ≥90%, 85-92% and 80-88% weed control, with crop injury rates of ≤3.0%, 3.0-4.5% and 3.5-5.0%, respectively, while European and American intelligent machines reach 92-98% weeding with 1.5-2.5% injury [3]. Reduced-dose integration is the other route that has been validated repeatedly. In maize trials by Fang Huimin et al., inter-row mechanical weeding achieved 83.4% weed control at the plant level, intra-row only 46.7%, and chemical control 96.2%; inter-row mechanical plus chemical treatment out-yielded mechanical-only and chemical-only plots by 29.0% and 20.4%, and the best result came from a 25% reduction in herbicide[36]. Bai Xuefeng reported something similar: mechanical weeding with 75% of the normal herbicide dose-controlled weeds as well as a full spray, yielded more than 36% above mechanical-only treatment, and caused only slight, manageable phytotoxicity[37]. For soybean-maize strip intercropping, Sheng Yi et al. designed a full-coverage trailed machine for the "2+4" configuration (two maize rows at 400 mm, four soybean rows at 300 mm, 600 mm between strips), matched it to a tractor with 1000 mm wheel spacing, and added depth control and row-correction mechanisms. The machine weeds several crop strips in one pass and suits the unusual row layout of strip intercropping, which offers a design basis for equipment in this system[38]. Huang Wenming et al. note that domestic weeders still perform poorly in efficiency, energy use and adaptability, and expect intelligent robots to be combined with mechanization in future[4].

Orchards. Weeding takes more labor than any other orchard operation, and mechanical weeding has become a focus because it is energy-efficient, safe and productive[16]. Suspended, ride-on, tracked self-propelled and intelligent machines are being developed in parallel, moving towards multifunction and automation. Obstacle avoidance within the row still relies mostly on mechanical feeler rods with hydraulic control. The automatic tree-avoiding device built by Zhang Bin et al. used a feeler to trigger a hydraulic mechanism; in field trials 100% of trees were passed and less than 6% of the area was missed[39]. Wang Zhenzhen et al. attribute China's orchard weeding problems to three sources-weak integration of machinery and agronomy, poor machine stability and reliability, and limited intelligence-and consider orchard weeding robots to be entering a period of rapid growth.

Open-field vegetables. Vegetables where the first setting in which laser weeding was verified, but narrow rows and little intra-row space often demand repeated passes, which makes the task harder than in field crops. Horticultural crops such as cabbage and lettuce were also the earliest targets of intra-row mechanical weeding: the vision-synchronized disc weeder of Tillett et al. was validated on transplanted cabbage[40], and the European studies summarized by Melander et al. likewise dealt mainly with cabbage, leek and onion[24]. Chinese work has shifted towards open-field cabbage in recent years. Zheng et al., from Jiangsu University and the

Beijing Academy of Agriculture and Forestry Sciences, developed an electric swing-type opening-and-closing intra-row system that reached 96.00% weeding accuracy with only 1.57% crop injury at 0.1 m/s; at 0.5 m/s accuracy dropped to 81.79% and injury rose to 5.49%[41]. The large difference between 0.1 and 0.5 m/s indicates that open-field vegetables are highly sensitive to operating speed.

Taken together, machine development is uneven across production settings. Paddy fields depend on standardized row spacing and show real promise for chemical-mechanical integration. Domestic upland machines still trail foreign ones, though mechanical-chemical integration has been shown to raise yield while cutting herbicide, and new systems such as soybean-maize strip intercropping exist only as prototypes. In orchards and open-field vegetables most equipment is still at the prototype stage, held back by poor machinery-agronomy matching and by the inherent trade-off between speed and accuracy. No mature machine has yet been shown to be suitable for widespread adoption, and fitting equipment to agronomic conditions remains the key to extending their adoption. 0 compares the performance, strengths and weaknesses of representative devices.

Table 1. Performance, advantages and limitations of representative mechanical weeding devices.

Device type	Weeding rate	Crop injury rate	Advantages	Limitations
Counter-rotating finger disc	64% (spinach, fresh-weight efficacy, 0.25 m rows)	None	Simple structure; weeds within the row	Efficacy well below thermal and chemical treatments
Combined unit (with finger wheel)	82.4% (field, Xinjiang)	2.65%	Flexible fingers roll weeds without injuring seedlings; suits compacted soil	Weeding rate constrained by soil condition
Pendulum	89.8% (soil bin, 0.6 m/s)	2.1%	Avoidance stroke can be programmed	Large reciprocating inertia; response lags at speed
Vision-guided hoeing robot	80% intra-row, >90% inter-row (multi-site, sugar beet)	Non-lethal burial up to 33%	Good control; commercially validated	Low work rate; high cost
Vertical rotary	89.57% (maize, 0.5 m/s)	4.54%	Avoids plants below the canopy	Speed limited to 0.5 m/s
Synchronized inter-/intra-row	83.6-88.34% (paddy, 0.7-0.8 m/s)	1.6-1.67%	Wide working width; good inter-row control	Paddy-specific; intra-row only 74.6%
Tactile vibratory	56.17% (paddy)	5.83%	No row-following required	Weeding rate clearly low
Water jet	-	Non-contact	No contact; no damage to rice (simulated erosion depth 37.61 mm)	No field weeding data
Laser	77% kill rate (field, targeted)	Non-contact	Precise; no soil disturbance	High cost; difficult to scale

Note: Values are representative trial results reported in the cited literature, with test conditions given in parentheses. Weeding rate, plant-level control efficacy, removal rate and kill rate are defined differently among studies, so comparisons across devices should be read together with the test conditions.

3. Analysis of existing problems

The literature suggests a field that is mature between rows, still struggling within rows, and under validation where intelligence is concerned. The gap between China and other countries is not really one of principle or algorithm-in mechanism design and recognition models, domestic work is close to the international level. It lies in three places. Commercial laser weeders and hoeing robots outside China have behind them years of multi-site commercial validation[29][34], while most domestic

results remain prototypes and plot trials, with little long-term evidence on the reliability and service life of tools. Datasets for crop-weed recognition are not shared, so models transfer poorly across regions and crops. Row-spacing standards and machine-friendly cultivation are not in place, and prototypes are hard to replicate elsewhere. The problems are grouped into four areas below.

3.1. Low intra-row weeding rate and high crop injury

Narrow intra-row space, with seedlings and weeds growing together, is the hardest part of mechanical weeding. Passive tools generally control only 40-65% of intra-row weeds[14], plant-level efficacy against intra-row weeds in maize is a mere 46.7%[36], and sensor less flexible vibratory weeding stays below 60%[30]. Selective devices reach 83-90%, but only when detection and localization are accurate enough, and their speed is usually limited: 0.25 m/s for a pneumatic unit[10] and 0.5 m/s for a vertical rotary one[25]. As speed rises, contact time between tool and weed shortens, the weeding rate falls and control accuracy drops, so crop injury climbs in turn[35]. Trials by Chen Xueshen et al. confirm that forward speed is the dominant factor in crop injury[11]. Compared with chemical control, the shortfall of purely mechanical weeding lies mainly in this intra-row band: between rows the tool can do the job, but within the row weeds are hard to distinguish and remove.

3.2. Unstable perception in complex environments and the gap between intelligence and engineering

Fluctuating light, lodged crops, complex soil backgrounds and differences in weed density all introduce errors into visual recognition, and these errors accumulate along the perceive-decide-act chain[13][42][43]. Recognition error and actuation delay end up as crop injury or missed weeds, and the conflict sharpens at high speed. Mechanical vibration, the rate at which images can be captured and the latency of data processing also constrain overall efficiency[13][42]. Cold-region rice areas pose a more specific problem: the growth period is compressed and the working window short, which further limits the time available to a vision system[43]. Deep-learning models have shortcomings of their own-annotation is costly, transferability across regions and crops is poor, datasets are neither shared nor reused, and most vision schemes are built for a single crop at a single growth stage[12][13]. More striking is the shift in research focus: most work addresses recognition and control algorithms, machine-level engineering validation is thin, and a gap has opened between academic exploration and industrial application[13].

3.3. Poor Machine Versatility and Weak Agronomic Fit

Machine design tends to be organized around a particular region and planting pattern, and versatility is limited across ridge tillage in the Northeast and flat

planting in the Huang-Huai-Hai region, between direct seeding and transplanting, and among row and plant spacings[3]. Walk-behind weeders have a working width of only 0.5-1.0 m and a weeding rate of 60-70%, so several passes are needed[44]. New systems such as strip intercropping impose further requirements, and weeding paths and machine width have to be replanned for the "2+4" row configuration[38]. Orchards are worse prepared for machinery: space under the canopy is cramped, conventional machines have insufficient clearance and damage trunks easily, which directly limits adoption[16]. Weak integration of agronomy and machinery is the immediate reason equipment fails to reach the field. Research effort is also unevenly distributed: domestic work concentrates on maize and rice, minor grain crops and cash crops receive much less attention, and many crops have no purpose-built machine at all.

3.4. Incomplete Validation Systems and Limited Industrialization

Inconsistent definitions are the most conspicuous problem. Weeding rate, plant-level control efficacy, removal rate and kill rate are used interchangeably, and plot size and survey timing vary; part of the wide spread in reported intra-row weeding rates, from 40% to 90%, stems from whether the denominator is the intra-row zone or the whole field[14][36]. Validation is thin as well: most intelligent equipment has been tested only in small plots or soil bins, some structural design studies report no field performance at all[3][31], and agreement between simulation and field results is rarely checked[32]. Cost and extension form another barrier. Intelligent equipment is expensive to buy, depends on skilled operation and continuing software maintenance, and smallholders can afford neither the outlay nor the risk of failure, which keeps the technology from spreading[13][43].

4. Development Strategies

The four problem areas point to four directions, taken in turn below.

1) For the low intra-row weeding rate and high crop injury, structural adaptivity should be combined with sensor-guided avoidance, with effort concentrated within the row. Field-validated mechanisms-vertical rotary, adaptive helical and combined units-should be further optimized to widen their tolerance of soil condition and plant spacing[15][25][27]; at the same time, control methods such as tactile start-stop and visual servo avoidance should be developed so that the intra-row weeding rate rises while injury stays at or below 5%[11][30]. Inter-row weeding is already relatively mature, at 83-90%, so research resources should shift towards the intra-row zone, and integrated machine validation of the two technologies should be given priority.

2) For unstable perception and the gap between intelligence and engineering, reliability should come before sophistication. GNSS/RTK, vision, LiDAR and inertial measurement units (IMU) should be fused and deployed in lightweight form at the

edge, so that recognition holds up under changing light and the reflections of paddy water[3][13]. Beyond algorithms, actuators that match advanced perception-avoidance manipulators and electro-hydraulic actuators-need to be developed in step[45]. Shared datasets and models for crop-weed recognition are also needed, to cut duplicated development and annotation cost[13].

3) For poor versatility and weak agronomic fit, the entry point is agronomy: cultivation patterns suited to mechanization should be explored and standardized. Row spacing and working-quality standards should be unified, and machine-friendly paddy fields and standardized orchards promoted[3][16]. A universal chassis with modular weeding tools would let one machine serve several crops and be reconfigured quickly[3][13]. Because smallholdings and fragmented plots dominate in China, large intelligent machines are difficult to introduce; lightweight, low-cost units that combine passive and active elements should be developed in parallel to broaden adoption at modest cost[44].

4) For incomplete validation and slow industrialization, national or industry standards covering intelligent weeders should be drafted promptly, core indices such as weeding rate should be defined consistently, and standards for row spacing, tillage depth and working quality in the main maize regions should be given priority[3]. A multi-level validation chain-simulation calibration, soil bin, plot, large-scale field-should be established, together with long-term monitoring of economic and ecological benefits[13][42]. For extension, the best-supported option at present is inter-row mechanical weeding combined with a 25-75% reduction in herbicide along the seed band[36][37][46]. Integrated machines that weed and spray in one pass should be developed to reduce the number of field operations and the cost of weeding, so that the returns from lower herbicide use lower the barrier to adoption.

5. Conclusions

Chinese agriculture is dominated by smallholdings, multiple cropping and a great many crops, with fragmented fields and wide crop diversity. That is the premise mechanical weeding cannot escape, and it is why the large-machine approach of European and American farms cannot simply be copied. Lightweight, modular and combinable equipment matched to real production conditions is the practical route for China. Mechanical weeding sits where green weed management meets herbicide reduction; research has deepened in recent years, and machine forms are converging towards intelligent integration. Several lines now run in parallel: passive tools, active avoidance devices, non-contact methods and sensing-based control. Inter-row weeding is close to mature, and intra-row intelligent weeding and mechanical-reduced-dose integration keeps producing advances. The weaknesses are equally clear-low intra-row weeding rates and high crop injury, unstable perception in complex environments, poor fit between machines and agronomy, and

incomplete validation, with most results still at the prototype or plot stage. Deeper integration of structural adaptivity with sensor-guided avoidance, reliable deployment of multi-sensor fusion and lightweight models, and standardization of machinery-agronomy practice should yield intelligent weeders that suit Chinese agronomy and combine mechanical weeding with reduced herbicide application, delivering efficient, low-damage and low-input precision weed management.

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