A REVIEW OF INTELLIGENT TOBACCO TRANSPLANTERS: KEY TECHNOLOGIES AND DEVELOPMENT TRENDS
/
烟草智能化移栽机械关键技术演进与发展趋势综述

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Abbreviations: *AI – artificial intelligence; CV – coefficient of variation; DEM – discrete element method; FPS – frames per second; GNSS – Global Navigation Satellite System; LCA – life-cycle assessment; LCC – life-cycle cost; MBD – multibody dynamics; MCU – microcontroller unit; MTBF – mean time between failures; MTTR – mean time to repair; PLC – programmable logic controller; RGB-D – red–green–blue plus depth; ROI – return on investment; UAV – unmanned aerial vehicle; YOLO – You Only Look Once.*

ABSTRACT
This review examines tobacco transplanting machinery, focusing on regional adaptation, automated seedling handling, planting mechanisms, coupled modeling, intelligent sensing, and field robustness. A narrative search covered English- and Chinese-language literature and standards through June 2026, selecting evidence by tobacco relevance or transferable similarity. High-throughput automation suits standardized production; hilly areas require compact, maneuverable, agronomically adaptable machines. Progress includes compliant seedling picking, buffered conveying, zero-relative-velocity planting, machine–soil–seedling modeling, machine vision, and digital twins. Constraints include seedling variability, adhesive soils, slope-induced disturbances, sensing degradation, and life-cycle cost. Future systems should integrate nursery standards, robust perception, decision-oriented digital twins, and modular electrification.

摘要
烟草移栽是连接育苗与大田生产的劳动密集型环节；丘陵碎片化地块、黏重红壤以及膜上移栽和井窖深栽等区域性农艺要求，进一步增加了装备适配难度。本文采用结构化叙述性检索，覆盖截至 2026 年 6 月的中英文文献与标准，并依据烟草相关性以及苗体形态、机构、土壤互作、感知任务或验证方法的可迁移性筛选证据。本文比较了不同区域的移栽装备技术路线，重点综述取苗、送苗、栽植、机-土-苗耦合建模以及感知与控制技术。研究表明，标准化平原或设施生产场景适宜采用高通量自动化装备，而丘陵烟区更需要小型化、模块化和高鲁棒性机具。现阶段的主要瓶颈包括钵苗一致性不足、高频作业与低损伤之间的矛盾、土壤黏附、传感器性能衰减以及较高的全寿命周期成本。未来应协同推进育苗标准化、柔性末端执行器、多模态感知、数字孪生和轻量化电动底盘的发展。

INTRODUCTION
Tobacco transplanting links nursery production to field establishment and directly affects plant spacing, planting depth, and early establishment. The global harvested area was approximately 3.2 million ha in 2023, with China accounting for roughly one third *(WHO, 2022; WHO, 2023a; WHO FCTC, 2025)*. Because the operation requires synchronized seedling separation, transport, soil or mulch penetration, placement, and covering, failure in one module can propagate through the entire cycle *(Jia et al., 2018; Wang X.B. et al., 2025; Yuan et al., 2023)*. Mechanization can reduce repetitive manual labor and improve spatial uniformity. Industry-wide fiscal data should not be interpreted as farm-level profitability, and labor-saving claims should still be considered alongside occupational and environmental costs *(IMTMA, 2024; WHO, 2023b)*. The present review therefore keeps these contextual issues concise and concentrates on the engineering problem.

These constraints are particularly acute in the hilly tobacco-growing regions of southwestern China, including Yunnan, Guizhou, and adjacent production areas. Fragmented plots, variable slopes, narrow access roads, and sticky red soils constrain machine dimensions and traction, while single-ridge, mulch-film, and well-cellar practices differ substantially from standardized vegetable transplanting. Historical national zoning data assigned 53.57% of tobacco planting area and 57.01% of commercial leaf volume to the Southwest tobacco-growing region *(Zhu, 2008)*. Because this regional classification is not equivalent to a slope-based definition and the data are historical, these percentages should not be interpreted as a current national share of 'hilly tobacco land'; no current nationally harmonized slope-class statistic was identified in authoritative public sources. Nevertheless, the historical concentration, together with continuing research on tobacco-specific crawler, electric, and well-cellar machines in these regions, demonstrates the engineering importance of hilly-area mechanization *(Bai et al., 2025; Wang B. et al., 2024; Xu L., 2024; Zhao Y., 2024)*. Consequently, a machine that performs well on level ground may lose planting-depth consistency, accumulate soil, or become difficult to maneuver on slopes.

Meanwhile, automated transplanting has progressed from purely mechanical mechanisms to compliant end-effectors, electromechanical control, machine vision, navigation, coupled simulation, and digital-twin-based quality monitoring. These advances create new opportunities but also reveal a persistent gap between laboratory performance and field reliability. High picking success obtained with uniform seedlings does not necessarily ensure stable operation when substrate moisture varies. Likewise, visual-detection accuracy may decline under dust, vibration, and rapidly changing illumination, and highly automated equipment may be economically unattractive when annual utilization is low *(Luo et al., 2022; Wang X.B. et al., 2025; Zhao Q. et al., 2026)*.

In this review, an intelligent transplanter is defined as a transplanting machine that uses sensing, state estimation, and/or programmable control to adapt seedling handling, mechanism timing, navigation, or quality decisions to observed conditions. Conventional and semi-automatic mechanisms are discussed as engineering baselines, compatible modules, or low-cost alternatives; they are not classified as intelligent unless they provide condition-aware or closed-loop functions. With this functional boundary established, the following paragraph explains how the evidence used to evaluate these machine functions was identified and screened.

The evidence base was assembled as a structured narrative review rather than a meta-analysis. Searches from database inception to 30 June 2026 covered Web of Science Core Collection, Scopus, Google Scholar, CNKI, and Wanfang, supplemented by citation tracing and publisher and standards websites. English and Chinese terms combined tobacco or plug seedling with transplanter, seedling picking or feeding, planting mechanism, well-cellar, vision or navigation, digital twin, DEM or MBD, field performance, safety, cost, and life cycle. Eligible records reported traceable evidence on mechanisms, modeling, sensing and control, safety, economics, or field performance; untraceable or engineering-irrelevant records were excluded.

Non-tobacco evidence was retained only when it shared an explicit engineering interface with tobacco: plug or root-block handling, planting trajectory, soil-tool interaction, sensing or control task, or validation method; crops are labeled in quantitative tables. Such evidence informs mechanisms, methods, and failure modes, not tobacco performance. Values are not treated as benchmarks unless crop, machine, seedling, soil, speed, and protocol are comparable.

Section 1 relates regional production conditions to machine architecture; Section 2 compares picking, conveying, and planting mechanisms; Section 3 evaluates coupled modeling, perception, AI, edge computing, and mechatronic integration; Section 4 examines deployment bottlenecks, safety, sustainability, and economics; Section 5 translates evidence gaps into short- and medium-term milestones; and the Conclusions summarize the review's principal contributions.

1. TECHNOLOGICAL ROUTES AND REGIONAL ADAPTATION

1.1 HIGH-THROUGHPUT AUTOMATION IN STANDARDIZED PRODUCTION

International tobacco-specific mechanization provides an important baseline. A U.S. self-feeding system handled cell-strand or bare-root material at about 100-140 plants/min under controlled conditions, while Japanese research developed a high-clearance mechanically fed tobacco transplanter *(Suggs et al., 1987; Asai and Miyake, 1989)*. European developments broadened this evidence base: an Italian DGNSS-RTK-assisted vine-cutting transplanter demonstrated automated georeferenced placement under different topographic conditions, and a precision three-row synchronized transplanter developed by Spanish/U.S. researchers addressed cross-row spatial and temporal coordination *(Mazzetto and Calcante, 2011; Pérez-*

Ruiz and Slaughter, 2021). These studies show that feeder reliability, positioning, and operator-machine coordination are system constraints. Robotic research subsequently established automated seedling-handling feasibility, with *Kutz et al. (1987)* representing an early milestone. Contemporary systems integrate perception, end effectors, and tray logistics: recent work used selective seedling assessment or plant-factory vision and automated tray handling *(Li M. et al., 2025; Liu W. et al., 2024b)*. The engineering question is whether the complete system can make reliable decisions at production speed.

High-throughput systems in protected horticulture commonly integrate tray indexing, parallel or multichannel handling, pneumatic assistance, and machine vision. Reviews of plug-seedling transplanting technologies indicate that protected-environment machines increase throughput by parallelizing picking and separating grading, transfer, and planting operations *(Habineza et al., 2023; Liu W. et al., 2023)*. Nevertheless, a higher nominal cycle frequency does not necessarily yield greater effective productivity. As seedling uniformity deteriorates, missed picks, substrate fragmentation, blockages, and operator interventions may increase rapidly. The appropriate design objective is therefore the maximum stable throughput sustained over an operating period, not the maximum instantaneous frequency.

The same principle applies to kinematic studies of dibbling and planting mechanisms. To control planting angle and uprightness, forward speed must be synchronized with the relative velocity between the planting component and the ground, the opening and closing phases of the planting element, and the instant of seedling release *(Iqbal et al., 2021)*. Compact, field-oriented automatic transplanters further demonstrate that robotic or mechanized picking can be integrated into multirow or mobile platforms. However, whole-machine performance continues to depend strongly on tray standardization, seedling mechanical properties, and reliable transfer between modules *(Ji D. et al., 2024; Khadatkar et al., 2023; Zhou et al., 2024)*.

1.2 COMPACT AND PRECISION-ORIENTED ROUTES FOR SMALL FIELDS

In East Asian production systems characterized by small, fragmented fields, equipment development places greater emphasis on compact dimensions, maneuverability, and repeatable mechanism timing. Compact electrically driven transplanters demonstrate how automatic conveying, picking, and planting can be integrated within a restricted machine width. Similarly, recent field tests of greenhouse cabbage equipment in Korea show that the capacities of the collection and transplanting modules must be coordinated at the system level *(Chen M. et al., 2025; Reza et al., 2025)*. Mechanical precision and compact integration remain attractive because they can reduce dependence on sensors; however, increased mechanism density makes accessibility, modularity, and maintainability more important.

Low-cost, manually assisted transplanters remain appropriate when farm scale, terrain, and service capacity do not justify full automation. Their engineering value lies in reducing repetitive bending, improving placement regularity, and increasing work rate without presuming that the most highly automated architecture is necessarily the most economical. In hilly tobacco-growing areas, semi-automatic guide-tube and duckbill machines may therefore remain competitive when they are lightweight, repairable, and tolerant of variable seedlings, even as fully automatic systems advance *(Jia et al., 2018; Wang X.B. et al., 2025)*. The relevant benchmark is the cost and quality per successfully transplanted area under local operating conditions, rather than the level of automation alone.

1.3 CHINA: FROM SEMI-AUTOMATIC MACHINES TO REGION-ADAPTED INTELLIGENT SYSTEMS

The development of Chinese tobacco transplanters has followed a region-adaptive pathway because production conditions differ markedly between the northern plains and the hilly southwest. Early integrated tobacco-machine designs established a foundation for mechanized transplanting *(Fei and Yan, 2018)*, while conventional guide-tube and duckbill machines remain useful where low cost and straightforward maintenance are priorities. Well-cellar production in hilly areas has stimulated the development of auger-type hole formers, electric drives, and tracked self-propelled platforms. Hydraulic and mechanical well-cellar systems, zero-relative-velocity planting concepts, and high-speed hole-forming devices have progressively addressed the requirements of deep planting and small mulch openings *(Fan et al., 2020a; Fan et al., 2020b; Jing, 2025; Wang L., 2025)*.

Automated seedling handling has advanced in parallel. Dual-tray staggered picking, compliant or pneumatic separation, multi-adaptive feeding, and low-cost motion-control architectures are intended to increase cycle frequency while limiting rigid contact with stems and substrate blocks *(Chen B. et al., 2024; Li G. et al., 2025; Shao et al., 2021; Zheng et al., 2025)*. Crawler platforms and microcontroller-based pneumatic control have lowered the entry barrier to field automation. Nevertheless, these field systems remain more sensitive than semi-automatic machines to seedling variability and environmental disturbances *(Bai et al., 2025; Li H.M. et al., 2024; Xu L., 2024)*.

Perception and autonomous functions are increasingly being integrated into this hardware base. Fuzzy control for missed-plant prevention, deep-learning-based seedling grading, GNSS/vision navigation, machine-vision-assisted low-damage handling, and tobacco-transplant recognition illustrate the transition from preset mechanism timing to condition-aware control *(Jin X. et al., 2020; Li T. et al., 2023; Liu Z. et al., 2026; Xin et al., 2022; Zhang S. et al., 2026)*. Digital-twin-based online quality inspection extends this concept by linking physical signals to predicted spacing, uprightness, and operating quality *(Zhao Q. et al., 2026)*. The central question is whether these functions remain reliable after prolonged exposure to dust, vibration, occlusion, and field variability.

Figure 1 summarizes this regional design logic. The comparison is not intended as a ranking of technological sophistication; rather, it shows that the preferred architecture depends on nursery-system standardization, field scale, terrain, agronomic practices, and local service capacity.

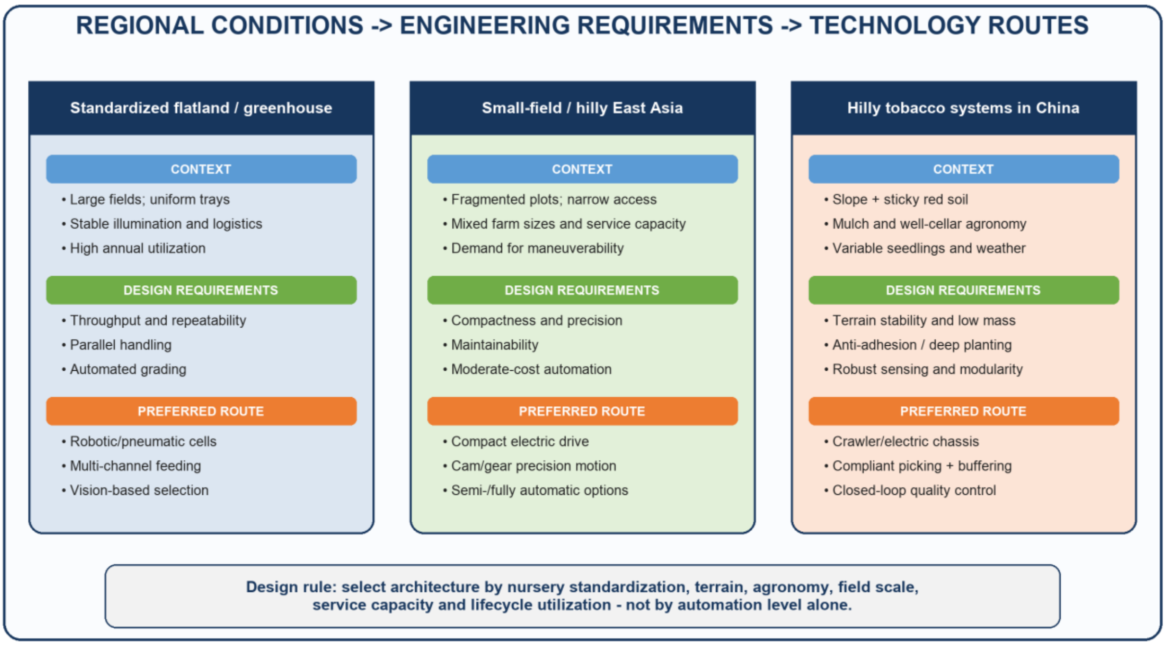

Fig. 1 - Regional production conditions and corresponding technological routes for transplanting machinery

Source: synthesized by the authors from the reviewed literature.

Table 1

Cross-regional comparison of transplanter development routes

Context / crop scope	Dominant objective	Typical technical route	Main strength	Key limitation for tobacco transfer
Protected systems vegetables; flowers	High stable throughput	Multi-channel robotic/pneumatic handling, vision grading	High cycle frequency and repeatability	Requires uniform trays/seedlings and stable environment
East Asia cabbage; vegetables	Mobility and precise motion	Compact chassis, gear/cam trajectories, moderate automation	Good maneuverability and mechanical repeatability	Complex transmissions; limited flexibility when agronomy changes
Low-capital systems tobacco; vegetables	Low cost and ergonomics	Manual or semi-automatic guide-tube/duckbill machines	Simple, repairable, low investment	Throughput limited by operator feeding
Hilly China tobacco	Agronomic adaptation and robustness	Crawler/electric chassis, well-cellar hole forming, flexible picking, sensing	Matches deep planting, mulch and slope constraints	Seedling inconsistency, soil adhesion and sensor reliability remain limiting

2. KEY MECHANISMS FOR AUTOMATIC TOBACCO TRANSPLANTING

2.1 SEEDLING PICKING: FROM RIGID GRIPPING TO FORCE-DECOUPLED EXTRACTION

Seedling picking is typically the first bottleneck encountered as the operating frequency of an automatic transplanter increases. Existing mechanisms can be classified broadly as direct-clamping or force-decoupled extraction systems. Direct clamping applies force to the stem or substrate block before removing the seedling from the tray. Although this approach offers a compact structure and short cycle time, its safe operating window depends on stem strength, root binding, substrate moisture, and adhesion between the substrate block and tray wall. Reviews and experimental studies consistently identify missed picks, stem damage, and substrate breakage as the principal failure modes *(Huang M. et al., 2023; Wang N. et al., 2021; Wang X. et al., 2023)*. Recent flexible multi-pin grippers further demonstrate that penetration geometry, squeezing force, and extraction speed must be optimized jointly rather than independently *(Han L. et al., 2025)*.

Trajectory and contact design can mitigate these failures. Oblique insertion followed by straight extraction, optimized cam paths, and whole-row mechanisms have been used to improve contact geometry and synchronize picking with downstream transfer *(Chen B. et al., 2024; Li Z., 2023; Xie et al., 2020)*. Coupled discrete-element and multibody simulations also allow mechanism–substrate interactions to be evaluated before physical prototyping *(Hou et al., 2023)*. A recent flexible gripper achieved reliable picking through oblique penetration, gradual squeezing, and vertical extraction, demonstrating the benefit of distributing contact through the substrate block rather than relying on a single rigid pull *(Han L. et al., 2025)*. Although reported success rates above 90% are encouraging, direct comparisons remain difficult because tray type, seedling age, substrate moisture, and even the definition of success are not standardized.

A second design strategy reduces stem loading by separating or redistributing the force required to detach the substrate block. Top-clamping-and-pulling, top-pushing/stem-clamping, and oblique multi-tine end-effectors either separate loosening from transport or distribute the extraction force across a larger root-block volume *(Hu J. et al., 2022; Liu W. et al., 2024a; Zhang N. et al., 2024; Zhang X.D. et al., 2023)*. For loose substrates, discrete-element calibration has been used to optimize an end-effector specifically for substrate mechanics, illustrating how material behavior can be incorporated directly into gripper design. Alternating dual-tray mechanisms can also reduce waiting time between operating cycles *(Liu C. et al., 2025)*. These benefits are obtained at the cost of a longer or more tightly coordinated action sequence and greater sensitivity to timing errors.

A notable shift in recent research is the use of plant and substrate mechanical properties instead of geometry alone. Studies of flexible multi-pin gripping, stem-damage modeling, and low-damage machine vision indicate that gripping force, penetration depth, impact acceleration, contact area, and substrate integrity should be treated as explicit design constraints *(Han L. et al., 2025; Xi et al., 2026; Xin et al., 2022)*. For tobacco seedlings, a useful next step would be to define a measurable damage envelope linking stem diameter, substrate moisture, root binding, and extraction resistance to allowable force and acceleration. Such an envelope would enable servo trajectories and compliant grippers to be tuned to the actual seedling batch rather than to a nominal specimen.

2.2 SEEDLING CONVEYING AND BUFFERING: DECOUPLING FAST PICKING FROM STABLE PLANTING

A high-frequency picking mechanism provides little benefit if seedlings reach the planter with an unstable orientation. Unconstrained free-fall transport can cause rolling and impact, whereas direct robot-to-soil placement assigns the manipulator responsibility for the entire cycle. Buffered or relay-type conveying offers a practical compromise by decoupling rapid tray-handling operations from the slower, near-zero-relative-velocity planting event. The buffer can absorb timing differences, correct orientation, and reduce the sensitivity of the planting mechanism to brief disturbances in seedling picking *(Fang et al., 2021; Shao et al., 2021)*.

Tray feeding and pre-loosening also require attention because high extraction resistance may dominate the failure rate. A rotary tray-feeding device that flexed the tray before picking reduced extraction resistance and improved picking success for rapeseed plug seedlings, illustrating how upstream tray mechanics can lessen the load on the end-effector *(Chen H. et al., 2025)*. Tobacco feeding devices based on structural guidance are intended to preserve seedling orientation during transfer, whereas compact automatic machines coordinate picking and feeding within a restricted spatial envelope *(Yan et al., 2020; Zhao X. et al., 2022)*. Flexible finger-and-chain conveying has produced similar benefits for fragile seedlings by reducing abrupt speed changes *(Ning et al., 2025)*.

Accordingly, the performance of a conveying system should be assessed using metrics broader than transport capacity alone. Relevant indicators include transfer success, orientation deviation at planter entry, residence-time variability, impact acceleration, and blockage probability over repeated cycles. This system-level perspective is particularly important for tobacco because large leaves may interfere with guides even when the substrate block is transferred successfully.

2.3 PLANTING MECHANISMS: MATCHING TRAJECTORY TO SOIL, MULCH AND PLANTING DEPTH

Duckbill planters remain widely used because a single mechanism can open the soil or mulch, receive and release the seedling, and initiate soil closure. Their principal kinematic requirement is to minimize horizontal relative velocity at the lowest point of the trajectory. Early elliptical-gear planetary mechanisms established deterministic noncircular transmissions as a means of shaping planting trajectories *(Chen J. et al., 2012; Yu G. et al., 2011)*. Tobacco-transplanter studies and subsequent mechanism optimization have focused on phase synchronization and the relationship between forward speed and release timing *(Iqbal et al., 2021; Ji J. et al., 2015; Xiong, 2025)*. Inadequate compensation for forward motion can elongate the planting hole, enlarge the mulch opening, or tilt the seedling. However, a purely kinematic optimum cannot represent resistance from the soil, mulch, or substrate block.

In mulch-film transplanting, the design problem extends beyond kinematics because the planting component interacts simultaneously with the film, soil, and substrate block. Studies of tobacco and other mulched crops show that planter geometry, penetration angle, and release control determine both film-opening size and seedling uprightness *(Li Y. et al., 2025; Yang W., 2019; Zhang W. et al., 2024)*. European field evidence from central Italy further showed 95-99% transplant success for savoy cabbage, fennel, and lettuce with a modified transplanter operating in both tilled and no-till soils, while also revealing crop- and spacing-specific skip risk *(Frasconi et al., 2019)*. Coupled machine-soil-pot models confirm that soil resistance and pot posture can shift the actual trajectory away from the ideal path *(Jin X. et al., 2025)*. Similarly, machinery-plant-soil modeling in rice transplanting demonstrates the value of representing impact and soil interaction when analyzing seedling damage *(Xue et al., 2022)*. Collectively, these studies indicate that a planting mechanism should not be optimized solely in a multibody model without a calibrated representation of the working medium.

Guide-tube and cup-type planters are structurally simpler and well suited to semi-automatic machines. In these systems, the seedling descends by free or constrained fall; tube inclination, inner-wall friction, and the opener's relative position determine its final orientation. High-speed imaging and dynamic analysis have been used to replace disordered tumbling with more stable sliding, while timing studies coordinate guide-tube discharge with planter opening *(Wu et al., 2022; Yin D. et al., 2021)*. This simplicity is advantageous in hilly tobacco production, although throughput remains closely coupled to manual feeding or upstream automatic orientation.

Well-cellar planting imposes a different engineering requirement: the machine must form a deep, narrow, and stable hole while minimizing wall collapse and mulch damage. Tobacco-specific planter and hole-forming studies have investigated auger rotational speed, penetration rate, soil discharge, anti-blocking geometry, planting-element design, and modal vibration *(Fan et al., 2020a; Fan et al., 2020b; Jiang X. et al., 2024; Liu W., 2017; Peng, 2025; Shi Y., 2023; Xu S. et al., 2024; Zhang D. et al., 2021)*. Recent continuous zero-relative-velocity well-cellar systems and high-speed dual-hole-forming devices seek to maintain hole quality as field capacity increases *(Jing, 2025; Wang L., 2025; Yang Y., 2025)*. A major remaining need is to relate hole geometry and wall stability to soil moisture and texture instead of validating a mechanism at a single soil state.

Table 2

Engineering comparison of key mechanism families

Mechanism / crop scope	Principle	Reported engineering advantage	Primary failure modes	Best-fit conditions	Priority metric
Direct clamp tobacco; pepper; tomato	Grip stem or substrate and extract directly	Short action chain; high potential frequency	Stem damage, substrate breakage, missed picking	Uniform seedlings with sufficient root binding	Success + damage severity + force margin
Eject + gripper tobacco; vegetables	Loosen block from below, then grasp	Lower peak extraction load; wider tolerance	Longer cycle; timing and alignment errors	Variable tray adhesion; fragile blocks	Extraction resistance + timing error
Buffer/relay tobacco; rapeseed; vegetables	Temporary storage and controlled handover	Decouples pick frequency from planting event	Orientation drift, blockage, impact	Automatic systems with multi-stage timing	Entry-angle deviation + impact acceleration

Mechanism / crop scope	Principle	Reported engineering advantage	Primary failure modes	Best-fit conditions	Priority metric
Duckbill tobacco; pepper; tomato	Penetrate/open/release/close in one cycle	Compact integrated operation; mulch compatibility	Dragging, large film tear, tilted seedlings	Mulched or bare soil with controlled trajectory	Relative ground speed + uprightness
Guide-tube/cup tobacco; vegetables	Seedling slides/falls into opened furrow/hole	Simple, inexpensive, maintainable	Rolling, collision, timing dependence	Semi-automatic and low-cost systems	Orientation at outlet + missed planting
Well-cellar auger tobacco	Rotary or impact formation of deep narrow hole	Matches deep-planting tobacco agronomy	Soil adhesion, blockage, wall collapse	Hilly tobacco regions using well-cellar planting	Hole geometry + wall stability + power

3. ENABLING TECHNOLOGIES FOR INTELLIGENT TRANSPLANTERS

3.1 MACHINE–SOIL–SEEDLING COUPLED MODELING AND COMPLIANT DESIGN

Multibody dynamics and discrete-element modeling have become important tools for moving transplanter design beyond trial-and-error geometry. Mechanism models are well suited to trajectory, acceleration, and phase analyses, whereas DEM represents soil and substrate-block contact. Coupling these approaches enables designers to evaluate how resistance and impact alter a nominal motion path. Applications include picking devices, planter–soil interactions, and hole-forming systems *(Hou et al., 2023; Jin X. et al., 2025; Zhang Q. et al., 2025)*. These methods are most informative when their parameters are calibrated against physical measurements rather than selected solely for numerical convenience.

The same principle applies to adhesion reduction. Sticky red soil can increase draft, prevent complete duckbill closure, and disrupt hole geometry. Studies of bionic microtextured tillage surfaces demonstrate that surface morphology can modify soil adhesion and resistance, suggesting a transferable strategy for tobacco-contact components *(Wang Z. et al., 2026)*. Future transplanting studies should therefore combine contact-angle or adhesion measurements with soil-moisture and texture characterization so that anti-adhesion surfaces are designed for a defined operating envelope.

Table 3

Quantitative evidence for coupled machine-soil-seedling modeling

Study / crop or system	Model / task	Validation	Reported quantitative evidence	Computational reporting used in this review
Jin et al. (2025), dryland vegetable pot seedlings (species not specified)	EDEM-RecurDyn; soil-pot seedling-planting device	Field comparison	Mean errors: soil backflow 2.14%; soil disturbance 2.46%; verticality 1.86%	Not ranked: platforms and computational-cost units were not harmonized
Hou et al. (2023), pepper	DEM-MFBD; pepper picking/depositing	Bench validation after coupled optimization	Picking success 97.92%; substrate loss 2.21%; errors versus regression predictions 0.49% and 3.8%, respectively	Not ranked: platforms and computational-cost units were not harmonized
Xue et al. (2022), rice	Machine-plant-paddy-soil numerical coupling	Physical transplanting validation (abstract-level evidence)	No numerical value reproduced because the full text was not accessible during this review	Not ranked: platforms and computational-cost units were not harmonized

Note: Full texts were available and checked for 2 of the 3 studies (Jin et al., 2025; Hou et al., 2023). For Xue et al. (2022), only the publisher abstract and indexed record were accessible; therefore, no numerical validation value was transcribed. Crop, soil, calibration, response variables, solvers, and coupling frameworks differ, so neither accuracy nor computational cost is ranked. Table 3 reports study-level evidence; proposed system gates appear in Table 7.

Compliant end-effectors constitute the mechanical counterpart to this modeling approach. Pneumatic, elastomeric, and force-limited grippers can attenuate impact and accommodate a broader range of seedlings than rigid clamps. Their performance should be evaluated in terms of force–displacement behavior, fatigue life, and contamination tolerance rather than short-duration laboratory picking success alone. In field machinery, a compliant element that is difficult to clean or whose stiffness changes after repeated cycles may introduce a new reliability problem.

3.2 PERCEPTION, NAVIGATION AND ONLINE QUALITY INSPECTION

Machine vision is used for seedling grading, selective picking, low-damage handling, planting-posture assessment, and missed-plant detection. Improved YOLO-based methods can distinguish seedling condition or transplanting targets, while RGB-D data support three-dimensional positioning and obstacle avoidance *(Li T. et al., 2023; Xin et al., 2022; Zhang S. et al., 2026; Zhao S. et al., 2022)*. More recent systems extend vision beyond recognition: selective transplanting uses perceived condition to determine which seedling to pick, YOLO-RDS estimates post-transplant uprightness, and UAV imagery combined with detection and tracking quantifies missed tobacco transplants at field scale *(Jin X. et al., 2024; Li M. et al., 2025; Su et al., 2025)*. These applications move perception toward a closed operational quality loop rather than an isolated classification task.

Research integrating machine vision with GNSS suggests a pathway toward autonomous field navigation *(Liu Z. et al., 2026)*. Nevertheless, tobacco transplanting involves disturbances that are underrepresented in many benchmark datasets, including large flexible leaves, changing canopy appearance, soil splash, mulch reflections, dust, and chassis vibration. The UAV-based tobacco study by *Su et al. (2025)* is particularly informative because it achieved useful field-scale evaluation while identifying limited scenario coverage as an unresolved generalization issue. Consequently, models trained under one agronomic background may attain high test accuracy yet exhibit lower operational availability when transferred to different soils, mulch conditions, or regions. Datasets should therefore represent disturbance levels and failure cases, and field studies should report the proportion of operating time for which the perception module remains valid.

Digital-twin-based quality inspection provides a framework for integrating physical signals, machine states, and predicted operating quality. A plant-factory transplanting study combined vibration data with virtual equipment models for online monitoring *(Chen K. et al., 2023)*, while broader agricultural-machinery research has described digital twins as bidirectional physical–virtual frameworks for equipment life-cycle applications *(Guo et al., 2023)*. Tobacco-specific research has further linked field and machine information to online quality indicators *(Zhao Q. et al., 2026)*. These layers should remain conceptually distinct: coupled DEM–MBD or other numerical models explain mechanisms, sensing estimates the current state, and a digital twin becomes operationally meaningful only when updated information supports parameter adjustment, fault warnings, or maintenance decisions within a useful time horizon.

Table 4

Reported perception performance (task-specific; not a universal leaderboard)

Study / task	Model	Reported accuracy	Speed / size	Robustness / comparison boundary
Su et al. (2025), tobacco UAV missed-plant assessment	YOLOv5s	P 75.1%; R 75.4%; mAP 75.8%	16.8 ms/image; 14.1 MB	Same self-constructed dataset; direct baseline
Su et al. (2025), tobacco - same dataset	YOLOv8s	P 72.6%; R 72.2%; mAP 72.9%	51.0 ms/image; 42.7 MB	Directly comparable with YOLOv5s; newer family was not superior here
Su et al. (2025), tobacco - same dataset	YOLOv11s	P 74.9%; R 75.1%; mAP 75.2%	17.8 ms/image; 19.6 MB	Directly comparable; accuracy close to YOLOv5s
Su et al. (2025), tobacco - same dataset	Improved YOLOv5s	P 79.0%; R 79.6%; mAP 81.1%	17.2 ms/image; 14.2 MB	With DeepSORT on field videos: Mm 4.1%, Mf 9.1%, MOTA 78.5%, 19.9 FPS; no cross-region test

Study / task	Model	Reported accuracy	Speed / size	Robustness / comparison boundary
Jin et al. (2024), vegetable seedlings (species not specified)	YOLO-RDS	mAP 97%; field accuracy 92.56%; mean relative error 3.09%	22 FPS	Absolute angle error 0–3°; different task/data, so not comparable with UAV rows

Within the shared dataset of *Su et al. (2025)*, YOLOv5s exceeded YOLOv8s in both mAP (75.8% versus 72.9%) and latency (16.8 versus 51.0 ms/image), demonstrating that a newer detector family is not automatically superior for small UAV targets. The improved YOLOv5s–DeepSORT pipeline yielded a missed-detection rate of 4.1%, a false-detection rate of 9.1%, a multiple-object tracking accuracy of 78.5%, and 19.9 FPS on field videos, but the single-site dataset does not establish cross-region robustness. Target-hardware testing is equally important: UAM-YOLO reported more than 175 FPS on its development platform but 10.57 FPS on a Qualcomm QCS6490 edge platform, illustrating the desktop-to-edge performance gap *(Su et al., 2025; Wang X.R. et al., 2026)*. Edge-deployment choices should therefore be based on end-to-end latency, energy consumption, thermal headroom, and operating-time availability rather than mAP alone. Compact convolutional detectors and sensor-fusion pipelines currently provide a stronger basis for deterministic real-time control than large language models (LLMs). LLMs may assist with maintenance-information retrieval, log summarization, and operator interaction, but safety-critical motion should remain under verified deterministic control. Cloud dependence also introduces latency, connectivity, and data-governance risks.

3.3 LOW-COST MECHATRONIC INTEGRATION AND FIELD ROBUSTNESS

The transition from prototype mechanisms to deployable intelligent machines depends on a control architecture that connects sensors, actuators, seedling-handling modules, and the chassis. Studies on the motion control of whole-row or reciprocating picking mechanisms have shown that shaped velocity profiles and coordinated multiaxis timing can reduce vibration at higher operating frequencies *(Shi J. et al., 2025)*. Integrated robotic systems likewise show that vision, tray logistics, and end-effector motion must be synchronized as a single production cycle rather than optimized independently *(Liu W. et al., 2024b)*. Automatic separation, air-assisted picking, and flexible feeding impose the same requirement for pneumatic–mechanical coordination *(Shao et al., 2021; Zhang B. et al., 2024; Zheng et al., 2025)*.

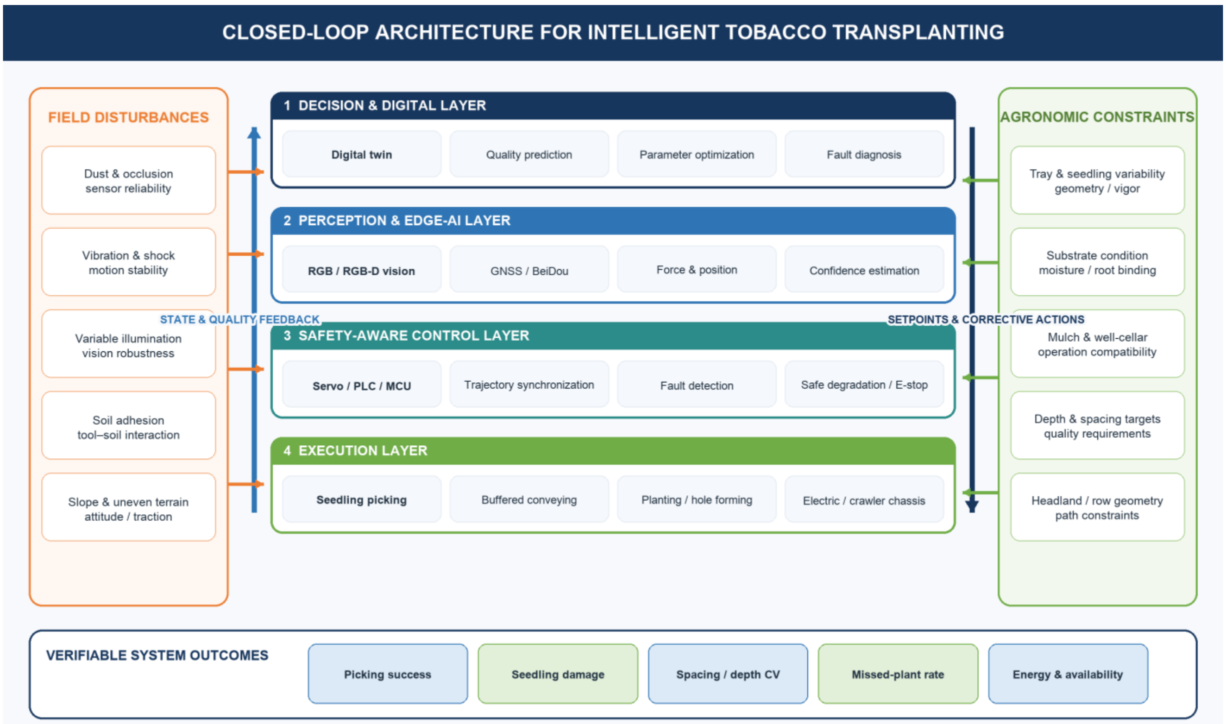

Fig. 2 - Closed-loop layered architecture, disturbance pathways, and performance feedback for intelligent tobacco transplanting

Source: synthesized by the authors from the reviewed literature.

For hilly tobacco production, control performance must be evaluated together with maintainability, energy consumption, and field availability. Industrial servos and PLCs may provide excellent laboratory control, but field machines must also tolerate dust, mud, voltage fluctuations, and maintenance by local service personnel. A miniaturized electrically driven plug-seedling transplanter demonstrated the practical advantages of compact electric actuation; however, its bench and field results also illustrate why module-level success should not be equated with whole-machine field performance *(Chen M. et al., 2025)*. Reviews of agricultural chassis for hilly and mountainous terrain further identify power, travel, steering, leveling, and navigation as coupled subsystems rather than independent design choices *(Jiang Y. et al., 2025)*. Lightweight electric tobacco platforms with microcontroller-based control should therefore be evaluated for slope stability, thermal load, battery endurance, contamination tolerance, and fault recovery over complete working days *(Bai et al., 2025; Li H.M. et al., 2024; Wang B. et al., 2024)*.

4. BOTTLENECKS FOR FIELD DEPLOYMENT

4.1 NURSERY–MACHINE MISMATCH AND AGRONOMIC DIVERSITY

The most fundamental barrier to fully automated transplanting often lies outside the machine itself. Seedling height, stem strength, root binding, substrate moisture, and tray geometry determine extraction resistance and the safe gripping window. When these properties vary, a mechanism optimized for one batch may cause missed picks or damage in another. Consequently, increasingly sophisticated end-effectors do not eliminate the need for nursery standardization *(Wang N. et al., 2021; Zhang X., 2021)*. A practical standard should specify not only nominal tray dimensions but also measurable tolerances for substrate integrity and seedling mechanical properties.

Agronomic diversity creates a second mismatch. Northern flatland tobacco may use ridge, row-spacing, and planting-depth configurations that differ from those used for well-cellar tobacco in the southwest. If the chassis, feeder, planter, hole former, and mulch-handling components are tightly integrated without standardized interfaces, a change in agronomic practice may require redesign of the entire machine. Modular connections, parameter-adjustable actuators, and software-defined timing can improve cross-regional reuse, provided that interface requirements are specified early in the design process.

4.2 HILLY TERRAIN AND ADHESIVE SOILS

Slope alters chassis attitude and, consequently, the penetration angle of the planting or hole-forming element. Wheel or track slip and shifts in the center of gravity can transform a well-tuned laboratory trajectory into an inclined hole or variable planting depth. Research on unmanned farms emphasizes that machine-friendly field infrastructure should be developed alongside autonomous equipment *(Luo et al., 2024)*. Similarly, a recent review of agricultural chassis for hilly and mountainous regions indicates that power, travel, steering, leveling, navigation, and path tracking must be designed as an integrated platform *(Jiang Y. et al., 2025)*. For hilly tobacco production, structural mass, track geometry, active or adaptive leveling, attitude sensing, and field accessibility should therefore be treated as system-level requirements rather than addressed by increasing traction power alone.

Sticky red soil imposes a direct tribological constraint. Soil accumulation on duckbills, press wheels, or augers increases resistance and may prevent complete opening or closing. Current well-cellar and hole-forming studies provide valuable kinematic and structural optimization, but field robustness must be validated across soil-moisture levels and repeated operating cycles *(Fan et al., 2020b; Jiang X. et al., 2024; Xu S. et al., 2024)*. Anti-adhesion microtextures, low-surface-energy coatings, and active cleaning devices are promising only if their durability, sensitivity to contamination, and effects on planting quality are quantified under representative red-soil conditions.

4.3 THE SPEED–DAMAGE–ROBUSTNESS TRADE-OFF

Increasing cycle frequency raises acceleration, inertial loading, and contact frequency, but the available literature quantifies speed–quality deterioration more often than direct plant injury. Direct injury evidence from rice seedling separation shows that the damaged stem-area ratio generally remained below 2% at 100–150 rpm, whereas at 300 rpm the median exceeded 8% for 40-day seedlings; maximum impact load and damaged-area ratio were strongly correlated ($\rho > 0.93$, $p < 0.001$) *(Xi et al., 2026)*. These results are seedling-age- and mechanism-specific and cannot be transferred quantitatively to tobacco. In a pepper transplanter, increasing the operating rate from 80 to 120 plants/min reduced overall transplanting success from 97.5% to 90.0% *(Chen M. et al., 2025)*. In a dryland tomato test, increasing the rate from 45 to 96 plants/min increased spacing CV from 6.6% to 8.9% and the missed-transplanting rate from 1.7% to 2.8% *(Wang Y.W. et al., 2018)*. Collectively, these findings support a speed–damage or speed–quality trade-off across crop-specific mechanisms, but they do not establish a nonlinear speed–damage curve for tobacco. The nonlinear-threshold hypothesis therefore remains to be tested in tobacco using matched seedling batches and direct injury measurements *(Chen Z. et al., 2026; Xi et al., 2026)*.

A comparable trade-off exists in sensing. Additional cameras and sensors can improve observability, but they also increase the number of failure points, calibration demands, and power consumption. In dusty, vibration-prone fields, robustness may be improved more effectively by combining a limited number of complementary sensors with self-diagnostics and confidence estimation than by simply adding channels. Field-grade intelligent transplanters should therefore support graceful degradation: when a perception module becomes unreliable, the machine should transition to a reduced but safe operating mode rather than stop unnecessarily or continue issuing erroneous commands.

Table 5

Empirical evidence for speed–quality trade-offs and damage risk

Study / crop	Operating rate	Observed response	Boundary of inference
Chen et al. (2025), pepper	80 → 120 plants/min	Overall success 97.5% → 90.0%; at 120 plants/min, picking 95.83% and depositing 94.78%	Direct speed sweep, but physical damage was not reported separately
Wang Y.W. et al. (2018), dryland tomato	45 → 96 plants/min	Spacing CV 6.6% → 8.9%; missed rate 1.7% → 2.8%	Direct speed sweep; quality loss, not a tobacco damage curve
Karayel et al. (2023), tomato/watermelon	0.4 m/s in the reported field protocol	Spacing CV 3.52–5.55%; only disc type damaged >3%; survival >90%	Mechanism comparison; no within-machine speed sweep
Xi et al. (2026), rice seedling separation	100–150 rpm versus 300 rpm	Damaged stem-area ratio generally <2% at 100–150 rpm; median >8% for 40-day seedlings at 300 rpm; $\rho(F_{max}, \text{damage}) > 0.93$ ($p < 0.001$)	Direct internal stem-damage evidence, but crop, seedling age and separation mechanism differ from tobacco field transplanting

The available evidence supports a speed–quality trade-off but does not establish a universal speed–damage relationship for tobacco. A defensible experiment should test at least three speeds on the same machine and seedling batch, report confidence intervals, and simultaneously quantify damage severity, missed plants, spacing CV, and field capacity.

4.4 ECONOMICS, MAINTAINABILITY AND SERVICE CAPACITY

A technically advanced transplanter may fail commercially if its capital cost and seasonal utilization are mismatched with farm scale. Full automation adds servomotors, pneumatic components, controllers, cameras, and wiring, increasing both manufacturing cost and the expertise required for troubleshooting. In fragmented tobacco-production systems, financial viability may depend on cooperative ownership or professional contracting services rather than individual purchase. Accordingly, cost per successfully transplanted hectare and annual machine availability are more informative deployment metrics than purchase price alone.

Maintainability should be treated as a primary design variable. Sensors and actuators should be accessible; connectors should be protected from mud and vibration; diagnostic information should be intelligible to field technicians; and critical spare parts should be standardized. Remote fault diagnosis may reduce downtime, but it cannot compensate for an architecture that is inherently difficult to inspect or repair. Region-adapted intelligent machines should therefore combine automation with an explicit service and maintenance strategy.

Table 6

Transparent LCC and ROI framework for intelligent transplanter adoption

Component	Included variables	Minimum evidence	Reporting rule
Annualized ownership	Purchase, financing, depreciation, insurance, housing	Local quotations and accounting records	Report currency/base year and discount rate

Component	Included variables	Minimum evidence	Reporting rule
Operating	Energy/fuel, labor, consumables, transport	Metered energy + time-and-motion records	Include charging losses and operator/support labor
Reliability	Planned service, failures, spares, downtime	MTBF, MTTR and seasonal availability logs	Value lost field windows explicitly
Benefit	Labor displaced, timeliness, quality/yield effects, service revenue	Matched field comparison	Do not monetize unmeasured yield gains
Decision	LCC/ha = discounted total cost / successful area; ROI = (discounted benefits - costs)/costs	Sensitivity by annual hectares and service life	Report break-even utilization, not purchase price alone

Published studies of tobacco transplanters rarely report comparable purchase prices, maintenance records, or annual utilization, so a tobacco-specific currency ROI cannot yet be calculated without speculative assumptions. European system analysis of agricultural robotics likewise identifies vehicle capacity and positioning-system cost as major economic drivers *(Pedersen et al., 2006)*. Cross-crop cases further demonstrate the controlling effect of utilization. A survey of six U.S. greenhouse firms evaluated a USD 125,000 transplant robot: under the average scenario, automated cost was USD 0.010 per cutting versus USD 0.014 manually, ten-year NPV was USD 105,807, and discounted payback was 4.8 years *(Adegbola et al., 2019)*. An Indonesian rice-transplanter rental case reported a break-even use of 27.96 ha/year, B/C ratio of 1.02, IRR of 20.79%, and payback of 4.84 years; increasing annual working days shortened the reported payback *(Asmara et al., 2024)*. These values are not transferable cost estimates for hilly tobacco because crop, wage, currency/base year, machine duty, and service model differ. Their transferable lesson is methodological: annual throughput, utilization, labor substitution, and service organization must be included explicitly. Table 6 converts this evidence into a reproducible tobacco field-data requirement for comparing individual ownership, cooperative ownership, and contracting scenarios.

The gates in Table 7 are provisional engineering targets, not standards or pooled estimates. The ≥95% picking-success gate is set below the best reported values used in this review: 97.92% for pepper in *Hou et al. (2023)*, 97.5% overall success at 80 plants/min in *Chen M. et al. (2025)*, and 95-99% transplant success across three vegetable crops in Italian tilled/no-till field tests by *Frasconi et al. (2019)*. The ≤3% damage/miss screen is consistent with 2.21% substrate loss in *Hou et al. (2023)* and a 2.8% missed-transplanting rate in dryland tomato at 96 plants/min in *Wang Y.W. et al. (2018)*. The 5% CV screen is informed by, but is not equivalent to, the 3.52-5.55% spacing CV reported for tomato/watermelon by *Karayel et al. (2023)*; it is not a validated tobacco depth limit. Because the reviewed studies did not report comparable full-period perception availability, seasonal availability, or fouling duration, the ≥95%, ≥90%, and ≥1 h values are protocol-design targets rather than literature bests and require multi-site calibration.

Table 7

Field bottlenecks, engineering responses and proposed validation thresholds

Bottleneck	Engineering response	Recommended validation	Why it matters	Exploratory gate (basis explained in text; not a standard)
Variable plug seedlings	Nursery tolerances + compliant/force-limited end-effector	Success rate, damage severity, extraction-force distribution across batches	Separates mechanism quality from unusually uniform test seedlings	Picking success ≥95%; damage ≤3% over ≥3 seedling batches
Slope and chassis attitude	Lightweight crawler, attitude sensing, self-leveling or trajectory compensation	Depth CV, uprightness, slip rate and stability on defined slopes	Directly measures field adaptation	Depth CV ≤5%; missed plants ≤3%; report defined slope classes
Sticky red soil	Anti-adhesion geometry/material + active cleaning	Draft/torque, adhesion mass, hole-quality decay over repeated cycles	Captures progressive fouling, not just first-cycle performance	Hole dimensions within agronomic tolerance after ≥1 h continuous work

Bottleneck	Engineering response	Recommended validation	Why it matters	Exploratory gate (basis explained in text; not a standard)
Dust/vibration/illumination	Multimodal sensing, confidence estimation, rugged mounting	Detection/navigation availability over full working period	Measures robustness rather than single-image accuracy	mAP plus ≥95% perception availability; safe fallback tested
High automation cost	Modular architecture and standardized components	Cost per hectare, annual utilization, MTBF/MTTR	Connects technical design with adoption feasibility	Seasonal availability ≥90%; MTBF/MTTR and LCC/ha reported

4.5 SAFETY, STANDARDIZATION AND HUMAN-MACHINE INTERACTION

Autonomous and electric transplanting introduces hazards beyond conventional guarding, including unintended motion, failure to detect people or obstacles, communication loss, battery thermal events, and unsafe recovery after sensor degradation. Internationally, ISO 18497 Parts 1–4:2024 address design principles, obstacle protection, autonomous operating zones, and verification for partially automated to autonomous agricultural machinery; ISO 25119 covers safety-related control systems; ISO 10975:2023 covers auto-guidance on operator-controlled machines; and IEC 62619:2022 addresses industrial lithium-battery safety *(ISO, 2024; ISO, 2019; ISO, 2023; IEC, 2022)*. In China, GB/T 39521-2020 covers agricultural auto-guidance but identically adopts the now-superseded ISO 10975:2009 edition, revealing an update gap relative to ISO 10975:2023. GB/T 16754-2021 specifies emergency-stop design principles, GB/T 41678.1-2022 covers higher-voltage electrical/electronic systems in agricultural machinery, and GB/T 46270-2025 specifies a BeiDou-based agricultural automatic-driving system. The mandatory general agricultural-machinery safety standard GB 10395.1-2025 has been published and is scheduled to take effect on 1 November 2026 *(SAC, 2020; SAC, 2021; SAC, 2022; SAC, 2025a; SAC, 2025b)*. A safety case for a tobacco transplanter should include accessible emergency stops, fail-safe stopping, guarded pinch points, battery isolation, ingress and thermal protection, audible and visual state indication, defined autonomous operating zones, obstacle detection, and documented residual risks. Compliance with general standards is necessary but not sufficient; machine-specific validation is still required on slopes, near workers, and during blockage clearing.

4.6 ENVIRONMENTAL SUSTAINABILITY AND LIFE-CYCLE BOUNDARIES

Electrification can eliminate machine-level tailpipe emissions and improve low-speed controllability, but its overall environmental benefit depends on the electricity mix, battery production and replacement, machine utilization, mass, service life, and end-of-life management. Consistent with ISO 14040 and ISO 14044, a comparative life-cycle assessment should state its goal and scope; define a functional unit, such as one successfully transplanted hectare; document inventory boundaries and data quality; and separate inventory results from impact assessment and interpretation *(ISO, 2006a; ISO, 2006b)*. The boundary should include embodied impacts of the machine and battery, energy supply and charging losses, maintenance, transport, interactions with mulch, and disposal, and should report both energy demand and greenhouse-gas emissions. Sensitivity analysis should vary battery life, annual utilization, electricity mix, and machine service life because these parameters can reverse comparisons between electric and combustion platforms. Design priorities include appropriately sized batteries, high-efficiency actuators, repairable modules, durable anti-adhesion surfaces, and battery take-back programs. These requirements prevent the label “electric” from being used as a sufficient proxy for sustainability.

5. RESEARCH PRIORITIES

First, nursery and machine design should be linked through measurable interface standards. Plug dimensions alone are insufficient; allowable ranges should also be specified for substrate moisture, root binding, stem diameter, seedling height, and extraction resistance. These specifications would allow end-effectors and feeding systems to be tested against representative variability rather than an idealized batch. Existing studies of picking, feeding, and damage provide a technical basis for developing such standards *(Wang X. et al., 2023; Xi et al., 2026; Zhang N. et al., 2024)*.

Second, compliant end-effectors should progress from passive flexibility to closed-loop interaction. Force or displacement sensing, elastic elements, and model-based motion profiles can regulate contact according to seedling and substrate conditions. Recent flexible multi-pin and DEM-optimized end-effectors provide useful starting points because they explicitly link geometry and operating parameters to root-block mechanics *(Han L. et al., 2025; Liu W. et al., 2024a)*. The objective is not to minimize gripping force unconditionally, but to maintain a robust force margin that guarantees extraction without damage. Closed-loop compliance should also be designed for contamination tolerance, fatigue resistance, and ease of cleaning.

Third, field perception should be evaluated in terms of operational availability and generalizability. Multimodal vision, depth sensing, and GNSS can complement one another, but the system should also estimate confidence and detect sensor degradation. Datasets and experiments must represent dust, mud, leaf occlusion, variable illumination, mulch reflections, and vibration. Post-transplant uprightness monitoring and UAV-based missed-plant assessment demonstrate that quality can be measured after planting; however, cross-scenario validity must be demonstrated rather than assumed *(Jin X. et al., 2024; Su et al., 2025)*. Ultimately, online quality inspection should update machine parameters or trigger corrective actions instead of remaining a post-operation monitoring layer *(Zhao Q. et al., 2026)*.

Fourth, machine–soil–seedling models and digital twins should be linked to experimentally verifiable decisions. DEM, multibody dynamics, and other coupled numerical models can predict contact forces, soil resistance, impact, and trajectory deviations; machinery–plant–soil modeling provides a transferable example of how damage mechanisms can be analyzed beyond ideal kinematics *(Hou et al., 2023; Jin X. et al., 2025; Xue et al., 2022)*. Digital twins add value when physical measurements update the virtual model and the resulting state estimate supports a decision, as illustrated by monitoring of transplanting equipment and broader agricultural-machinery frameworks *(Chen K. et al., 2023; Guo et al., 2023; Zhao Q. et al., 2026)*. A meaningful closed loop should adjust penetration timing, motion profiles, cleaning intervals, or maintenance actions and subsequently demonstrate improved planting quality or a lower failure rate.

Fifth, platforms for hilly regions should prioritize lightweight, modular electrification. Electric drives simplify low-speed control and support distributed actuation, while modular planters, feeders, and hole-forming units allow one chassis to serve multiple agronomic configurations. Research on miniaturized electric transplanters and reviews of agricultural chassis for hilly terrain provide a practical basis for integrating electric drive, compact packaging, leveling, and navigation instead of treating electrification as battery substitution alone *(Chen M. et al., 2025; Jiang Y. et al., 2025)*. The engineering challenge is to balance energy capacity, slope safety, structural mass, and serviceability. Crawler and electric tobacco-transplanter studies provide a tobacco-specific basis for this development *(Bai et al., 2025; Wang B. et al., 2024; Zhao Y., 2024)*.

Finally, the field requires common reporting protocols. Studies of seedling picking should report seedling variability, picking success, damage, and force-related indicators. Planting studies should report depth, spacing, uprightness, missed-plant rate, and mulch damage under defined soil and speed conditions. Evaluations of intelligent functions should report full-period availability and recovery from faults in addition to algorithmic accuracy. Consistent reporting would help distinguish genuine technological advances from performance that depends on favorable test conditions.

Table 8 applies the same provisional gates as research milestones, not current tobacco standards; medium-term availability targets must be recalibrated from multi-region seasonal data.

Table 8

Measurable short- and medium-term research milestones

Priority	Short-term horizon	Short-term measurable milestone	Medium-term horizon	Medium-term measurable milestone
Nursery-machine interface	0-2 y	Measure extraction force, moisture, stem diameter and root binding across ≥3 batches	3-5 y	Inter-laboratory protocol and crop/region-specific tolerance bands
Closed-loop compliant picking	0-2 y	≥95% success and ≤3% damage across defined batch variability	3-5 y	Full-day field validation with fatigue/contamination and fault recovery
Robust perception/edge AI	0-2 y	Public disturbance-labeled dataset; latency, energy and availability reported	3-5 y	Cross-region validation with ≥95% operating-time availability and safe degradation
Models/digital twins	0-2 y	Report calibration, error, hardware and wall-clock cost	3-5 y	Online parameter or maintenance decision shown to improve field KPI

Priority	Short-term horizon	Short-term measurable milestone	Medium-term horizon	Medium-term measurable milestone
Electric/autonomous platform	0-2 y	Battery endurance, slope stability, emergency-stop and obstacle tests	3-5 y	Seasonal LCC/LCA plus standards-aligned autonomous-zone validation
Common reporting	0-2 y	Core KPI dictionary and minimum test metadata	3-5 y	Multi-site benchmark with shared protocols and uncertainty intervals

CONCLUSIONS

Tobacco transplanting machinery is evolving from mechanism-centered equipment into integrated systems that couple nursery quality, seedling handling, soil interaction, chassis motion, sensing, and control. The available international evidence indicates that no single transplanter architecture is universally superior: high-throughput automation is effective in standardized production, whereas hilly tobacco-growing areas require compact, maneuverable, and agronomically adaptable machines.

At the mechanism level, the most important transition is from rigid, single-action designs to force-decoupled picking, buffered conveying, and planting trajectories that explicitly account for soil and seedling interactions. Reported high success rates demonstrate technical feasibility, but field performance remains difficult to compare because seedling properties, soil conditions, and disturbance levels are not reported consistently.

For intelligent tobacco transplanters, the principal bottleneck is system robustness rather than the availability of individual algorithms. Vision, navigation, coupled simulation, and digital twins will have practical value only if they remain functional under dust, vibration, slope, and soil adhesion and if their outputs trigger corrective machine actions. The next generation of equipment should therefore integrate nursery standardization, compliant end-effectors, rugged multimodal sensing, decision-oriented digital twins, and lightweight modular electric chassis, while treating life-cycle cost and maintainability as explicit design objectives.

The key takeaways arising from these conclusions are:

(1) Machine architecture should be selected according to terrain, agronomic practice, nursery uniformity, service capacity, and annual utilization; automation level alone does not define a performance hierarchy.

(2) Cross-crop technology transfer is most defensible at the level of mechanisms, sensing methods, and validation protocols; tobacco-specific constraints associated with well-cellar planting, mulch, and hilly soils still require dedicated field tests.

(3) DEM–MBD models, perception systems, and digital twins are useful only when simulation error, computational cost, field availability, and decision benefit are reported together.

(4) Available evidence supports a speed–quality trade-off, but no universal speed–damage curve has been established for tobacco; matched, multispeed experiments should therefore be prioritized.

(5) Safety, LCC/ROI, and LCA should be treated as design inputs for electric and autonomous machines rather than as post hoc claims.

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