HYDRAULIC TECHNOLOGY IN TUBER CROP MECHANIZATION: APPLICATIONS, CHALLENGES, AND RESEARCH PROGRESS

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液压技术在薯类作物机械化中的应用与挑战研究综述

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ABSTRACT

Hydraulic drives are widely used in tuber crop machinery for travelling and working-unit operations to cope with complex field conditions. However, under low-speed high-torque operation, fluctuating loads, and multi-actuator working conditions, hydraulic systems often suffer from reduced energy efficiency and insufficient stability. This paper reviews typical applications of hydraulic technology in travelling and working-unit drive systems of tuber crop machinery, and analyzes key issues including energy efficiency under low-speed high-torque conditions, dynamic responses to load fluctuations, system coupling induced by multi-actuator operation, and stability constraints related to crop damage sensitivity. Recent advances in system optimization and control strategies are summarized.

摘要

薯类作物机械在挖掘、输送、分离及行走等作业环节中广泛采用液压驱动，以适应复杂多变的田间工况。然而，在低速大扭矩作业、负载强波动及多执行机构并行运行条件下，液压系统易出现能效下降、压力与流量波动加剧及驱动稳定性不足等问题。围绕薯类作物机械的作业过程与动力需求特征，本文系统综述了液压技术在行走驱动系统与作业部件驱动系统中的典型应用，重点分析了低速大扭矩工况下的能效特征、负载波动引发的动态响应、多执行机构并行运行的系统耦合效应以及作物损伤敏感性对驱动稳定性的约束作用。在此基础上，总结了液压驱动系统在结构优化、功率匹配、负载敏感与电液控制、多执行机构协同控制及信息融合辅助控制等方面的研究进展，旨在为薯类作物机械液压系统的优化设计与控制策略研究提供参考。

INTRODUCTION

Tuber crops, such as potato and sweet potato, are widely cultivated worldwide and constitute important staple food and cash crops *(Cui et al., 2026; FAO, 2008; FAO, 2012; Zhou et al., 2026)*. Their extensive cultivation and stable production impose high demands on the adaptability and reliability of agricultural machinery. Unlike above-ground crops, tuber crop mechanization involves multiple operation stages, particularly during harvesting, where digging, separation, conveying, and cleaning are performed simultaneously under low travelling speeds and highly fluctuating loads. In addition, tubers are mechanically sensitive, and the stability of power transmission and actuator motion plays a critical role in ensuring operational efficiency and product quality *(Mohsenin, 1986)*.

In tuber crop mechanization, hydraulic systems are widely applied due to their inherent engineering advantages, particularly in travelling drives, working-unit actuation, and multi-actuator systems *(Merritt, 1967; Liljedahl et al., 1989)*. *Pedersen et al., (2004),* reviewed load-sensing (LS) hydraulic systems, covering conventional and electro-hydraulic LS as well as alternative concepts, and outlining future research directions; *Renius et al., (2003),* systematically summarized hydrostatic drive transmissions for mobile machinery in terms of architecture, design rules, and typical efficiency, including direct and power-split configurations; *Mahato and Ghoshal, (2020),* categorized energy-saving routes for hydraulic drive systems, highlighting hybridization, advanced control, energy recovery, and loss reduction. However, under low-speed high-torque and frequently varying operating conditions, hydraulic systems often exhibit reduced energy efficiency and degraded dynamic performance, manifested by pressure fluctuations and response delays.

These issues not only constrain further improvement of machine performance but may also exacerbate mechanical damage to tubers during harvesting operations *(Ivantysyn & Ivantysynova, 2003; Bentini et al., 2006; Ding et al., 2019)*.

In recent years, extensive studies have addressed working-unit optimization, separation and conveying mechanisms, and crop damage evaluation in tuber crop mechanization *(Bentini et al., 2006; Li et al., 2022; Li et al., 2025; Zhang et al., 2024)*, alongside notable progress in hydraulic drive and control technologies *(Helbig et al., 2018; Linjama & Vilenius, 2016)*. However, most existing research remains fragmented and machine-specific, and a comprehensive review of hydraulic technology covering application patterns, common bottlenecks, and development trends throughout the mechanized production process of tuber crops is still lacking *(Helbig et al., 2018; Zhou et al., 2019)*.

This paper reviews typical applications of hydraulic technology in key operations of tuber crop mechanization, with a focus on energy efficiency and control issues under low-speed high-torque conditions, fluctuating working loads, and crop damage sensitivity. Recent advances in hydraulic system optimization, electro-hydraulic control, and intelligent applications are summarized, and representative engineering cases are discussed to identify development trends and provide reference for the design and improvement of related equipment. To ensure structural consistency and comparability, this review is organized along a “functional modules-control architectures-engineering constraints” framework, with cross-comparisons among representative configurations including open/closed circuits, pump/valve control, and load sensing (LS). Building on typical engineering cases, development trends in hydraulic technologies for tuber-crop mechanization are further distilled to inform system optimization and equipment improvement.

TYPICAL APPLICATIONS OF HYDRAULIC TECHNOLOGY IN TUBER CROP MECHANIZATION

In tuber crop mechanization, hydraulic systems play a central role in power transmission and motion control across travelling drives, working units, and multi-actuator systems. Owing to heterogeneous load characteristics, operating modes, and crop damage sensitivity, hydraulic systems are subject to diverse functional requirements and engineering constraints. To clarify their application characteristics from a system perspective, this paper reviews hydraulic applications in travelling drives, working units, and multi-actuator coordination, aiming to identify common requirements and key issues that underpin subsequent analysis of performance bottlenecks and optimization strategies. From a system-architecture viewpoint, hydraulic drives in tuber-crop machinery can be described within a unified taxonomy-circuit topology, speed-regulation mechanism, and control strategy—to compare scenario-specific performance limits. Open-circuit systems offer straightforward, flexible layouts but are typically more throttling- and heat-prone at low-speed high-torque operation, whereas closed-circuit systems provide higher transmission efficiency and smooth continuous speed control for travel drives, at the cost of stricter charge, cooling, and stability design. By regulation mechanism, valve control is fast and cost-effective yet concentrates losses in throttling power (pressure drop × flow), making efficiency deterioration severe in low-flow/high-pressure-drop regions; pump control reduces throttling via displacement-based supply matching but is bandwidth-limited in transients; pump–valve hybrid schemes trade efficiency for dynamics via pump-side matching with valve-side trimming. By strategy, load sensing (LS) improves operability through pressure-margin regulation but may exacerbate inter-branch coupling in parallel multi-actuator systems sharing a pump, inducing coupled pressure–speed oscillations. This framework is used to map travel drives, working-unit drives, and coordinated multi-actuator control to clarify efficiency constraints, dynamic limits, and stability risks.

Hydraulic Applications in Travelling and Driving Systems

In tuber crop mechanization, the travelling system provides traction and motion stability for the whole machine. Potato harvesting is usually conducted at low travelling speeds under strongly fluctuating loads influenced by soil conditions and crop distribution, which requires the travelling system to deliver smooth and continuous power output to avoid instability of working units and aggravated tuber damage *(Ucgul et al., 2015; Bentini et al., 2016; Zhou et al., 2019)*. Accordingly, the hydraulic system serves as the core power transmission and control unit of the travelling system (Fig.1).

In engineering practice, hydraulic travelling drives are widely adopted in tuber crop harvesting equipment, especially in self-propelled potato and sweet potato harvesters, due to their suitability for low-speed, high-torque operation and variable load conditions *(Fan et al., 2025)*.

A typical solution is hydrostatic transmission, in which stepless speed regulation is achieved through pump displacement or flow control, enabling stable traction output at extremely low travelling speeds *(Ivantysyn & Ivantysynova, 2017; Wang et al., 2024)*. As a result, hydraulic travelling drives exhibit good controllability under complex field conditions and meet the speed stability requirements imposed by digging and separation operations *(Van Canneyt et al., 2004; Ivantysyn & Ivantysynova, 2017)*.

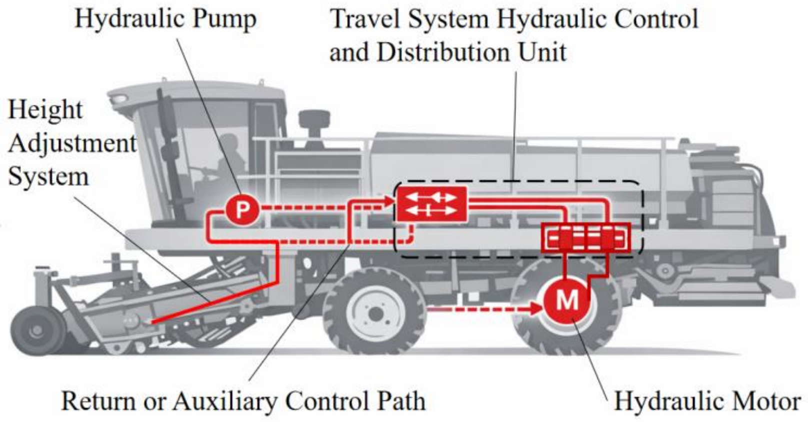

Fig. 1 - Typical functional schematic of hydraulic drive in the travelling system of tuber crop harvesting equipment

With increasing functional integration of tuber crop harvesting equipment, distributed hydraulic travelling drive solutions have been increasingly adopted, in which multiple travelling motors operate in parallel with working-unit circuits *(Rossi et al., 2023; Fan et al., 2025)*. Under such configurations, the travelling system shares a common power source with multiple actuators, leading to pronounced multi-load coupling effects *(Rossi et al., 2023)*. Although distributed drives improve machine passability and layout flexibility, they are more susceptible to circuit coupling and abrupt load variations, typically manifested as amplified pressure fluctuations and delayed speed responses, thereby imposing higher demands on system energy efficiency and control strategies *(Xu & Cheng, 2018; Rossi et al., 2023)*. Especially in parallel systems powered by load sensing (LS) or dominated by multi-branch valve throttling, the interplay between flow redistribution and pressure-margin regulation can amplify cross-branch interactions, increasing the coupling between pressure and speed fluctuations.

For trailed or semi-mounted tuber crop implements, hydraulic systems are mainly used for auxiliary propulsion and attitude adjustment rather than as the primary traction source *(Kutzbach & Quick, 2021; Blok et al., 2025)*. Hydraulic adjustment of travelling or supporting wheels enables dynamic control of working depth and machine attitude, thereby alleviating the effects of non-uniform field resistance on digging quality *(Kutzbach & Quick, 1999; Kutzbach & Quick, 2021)*. Although traction is provided by the tractor, the operational stability and coordination of such systems remain strongly dependent on the dynamic response of the hydraulic system *(Wang et al., 2021; Bhola & Wrat, 2026)*. Table 1 summarizes typical hydraulic travelling drive configurations and their operating characteristics.

Table 1

Comparison of typical hydraulic travelling drive configurations and their characteristics in tuber crop harvesting equipment

Hydraulic travelling drive configuration	Typical application scenarios	Operating condition characteristics	Main advantages	Main constraints
Closed-circuit hydrostatic travelling drive	Self-propelled tuber crop harvesting equipment	Low speed, high torque, pronounced load fluctuations	Good stepless speed regulation performance, high low-speed control accuracy	Energy efficiency sensitive to load variations, high system complexity
Distributed hydraulic travelling drive	Multi-driven wheel or tracked chassis	Parallel operation of multiple actuators, complex load distribution	Flexible layout, strong traction adaptability	High degree of circuit coupling, complex control
Hydraulic-assisted traction drive	Trailed tuber crop implements	Traction-dominated operation, relatively stable travelling load	Simple structure, controllable cost	Limited primary driving force, restricted speed regulation capability

Overall, hydraulic travelling drive systems in tuber crop machinery are valued for their capability to operate under low-speed, high-torque conditions and to accommodate complex load variations *(Wang et al., 2021)*. However, under long-term heavy loads and multi-loop parallel operation, such systems often suffer from reduced energy efficiency and degraded dynamic stability, which have become key constraints on further performance improvement and motivate subsequent analysis of energy efficiency characteristics and control strategies.

Hydraulic Applications in Working Component Drive Systems

In tuber crop harvesting equipment, hydraulic technology is widely used in working component drive systems responsible for operations such as digging, conveying, and separation *(Li et al., 2020; Li et al., 2025; Zhang et al., 2015).* Direct interaction with the soil–crop mixture causes these components to operate under low-speed, strongly nonlinear, and stochastic load conditions, which require both high transient capability and stable speed regulation. Owing to their high power density, overload adaptability, and suitability for multi-actuator coordination, hydraulic drive systems are therefore preferred over mechanical or purely electric alternatives *(Pustavrh et al., 2023; Zhang et al., 2024)*.

Hydraulic Drive Applications in Excavation Components

The excavation component is the first working unit of tuber crop harvesting equipment to interact with the soil *(Bao et al., 2024; Yue et al., 2020).* As shown in Fig. 2, its primary functions include soil cutting, crop lifting, and preparation for subsequent separation and conveying. Due to variations in working depth and soil mechanical properties, excavation resistance exhibits pronounced time-varying characteristics, which can induce significant load fluctuations in the drive system *(McKyes, 1985)*. In engineering practice, excavation shovels, cutting discs, and vibrating digging devices are commonly driven and adjusted by hydraulic motors and cylinders *(Kutz, 2013)*, enabling high torque output at low speeds and real-time depth and attitude adjustment. Although such hydraulic configurations enhance adaptability and operational stability under complex soil conditions, inherent load variations may still lead to pressure fluctuations in the hydraulic system *(Huo et al., 2023; Jovanović et al., 2024)*. In terms of speed regulation, achieving low-speed high-torque output for digging/cutting units via valve throttling tends to incur substantial throttling losses under large pressure drops; using variable-pump supply or pump–valve hybrid control can reduce throttling while maintaining output capability, although transient response is constrained by pump-actuation and controller bandwidth.

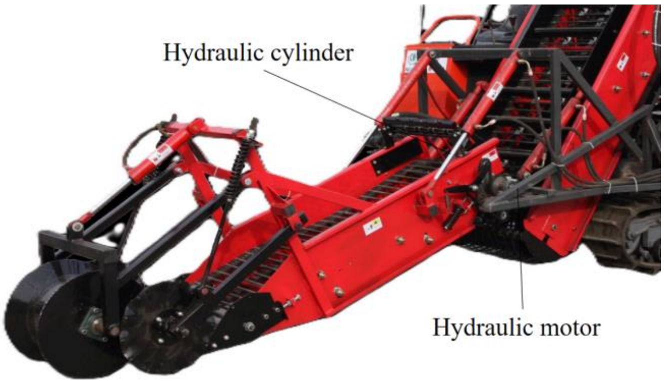

Fig. 2 - Excavation device of a potato harvester

Hydraulic Drive Applications in Conveying and Separation Devices

The conveying and separation system is a key functional module in tuber crop harvesting machinery, directly affecting separation efficiency and crop damage *(Gao et al., 2020; Shen et al., 2020; Yang et al., 2024; Zheng et al., 2025).* It typically consists of multi-stage conveying and screening components driven by multiple actuators operating continuously, which leads to pronounced coupling among subsystems under variable working conditions *(An et al., 2025).* In engineering practice, hydraulic motors are widely used to drive conveying and separation devices, enabling stepless speed regulation and improved adaptability to varying soil impurity levels and crop flow conditions. Compared with rigid mechanical transmission, hydraulic drives help alleviate transient shocks and reduce stalling risks, thereby mitigating tuber collisions and compression. However, when multiple conveying stages operate in parallel, flow distribution imbalance and load coupling among hydraulic circuits become more pronounced, imposing higher demands on system matching and control strategies *(Fan et al., 2025; Rossi et al., 2013)*.

Hydraulic Applications in Cleaning and Auxiliary Work Components

In addition to core working units, tuber crop harvesting machinery is commonly equipped with auxiliary mechanisms such as lifting, bag handling, and attitude adjustment, which are predominantly actuated by hydraulic cylinders *(Wei et al., 2023; Yang et al., 2020).* These systems typically operate under relatively stable loads with frequent motions and high requirements for speed accuracy and synchronization. Hydraulic auxiliary systems enhance operational adaptability and enable rapid switching between working and transport modes. Although their power demand is generally low, their dynamic response can still influence overall machine continuity, particularly when multiple subsystems operate in parallel and contribute to system-level load fluctuations *(Ivantysyn & Ivantysynova, 2003)*. At the control-strategy level, multi-cylinder coordination and attitude regulation typically rely on proportional valves or electro-hydraulic control for smooth actuation; performance is affected by valve deadband and hysteresis as well as supply-pressure stability, and thus requires particular attention to system-level transmission of pressure fluctuations when operating in parallel with highly varying digging/transport circuits.

Summary

Overall, hydraulic drive systems for working components in tuber crop machinery exhibit clear engineering advantages in accommodating complex loads and coordinating multiple actuators. However, with increasing functional integration and parallel operation of multiple subsystems, issues related to load coupling, energy efficiency degradation, and dynamic stability have become increasingly prominent, forming the practical basis for subsequent analysis of hydraulic system energy characteristics and control strategies.

WORKING CONDITION CHARACTERISTICS AND TYPICAL ISSUES OF HYDRAULIC SYSTEMS IN TUBER CROP MACHINERY

Based on the preceding review, hydraulic drives are deeply integrated into both travelling and working component systems of tuber crop machinery, enabling stable operation under complex field conditions. However, the performance limitations of hydraulic systems arise not from individual components or machine types, but from the combined effects of operating conditions and system-level operating modes. Tuber crop machinery typically operates under low-speed, high-load conditions, where long energy transmission paths, complex power matching, and stochastic load variations amplify pressure and flow fluctuations and degrade dynamic response *(Watton, 2009; Xu & Cheng, 2018)*. In parallel multi-actuator configurations, coupling effects through shared hydraulic circuits further constrain energy efficiency and control performance *(Bhola & Wrat, 2025)*. Moreover, the high sensitivity of tuber crops to mechanical impacts imposes stricter requirements on drive stability, as speed fluctuations and transient shocks may aggravate crop damage under alternating loads *(Zhu et al., 2025)*. These characteristics highlight the necessity of systematically analyzing low-speed, high-torque operation, load fluctuation response, and multi-actuator coordination to establish a clear problem framework for subsequent hydraulic system optimization and control strategy research.

Energy Efficiency Characteristics under Low-Speed and High-Torque Operating Conditions

During field operation, tuber crop machinery typically requires both travelling drives and working units to deliver high tractive forces and operating torques at low forward speeds, resulting in prolonged low-speed, high-load operation of the hydraulic system *(Ivantysyn and Ivantysynova, 2003)*. Under such conditions, hydraulic energy transmission exhibits pronounced non-ideal characteristics, and system efficiency becomes highly sensitive to pressure levels, flow regulation methods, and circuit configuration. Unlike medium- and high-speed operation, low-speed, high-torque conditions often lead to increased throttling losses and enlarged pressure differentials, resulting in higher energy consumption per unit output power *(Bhola, 2025)*. To provide a testable explanation for why energy consumption increases, the system efficiency can be expressed as the ratio of pump-supplied power to the effective load power:

Pump-supplied power:

$$\mathrm{P_p = p_p \cdot Q_p} \tag{1}$$

Effective load power (hydraulic motor example):

$$\mathrm{P_L = T_m \cdot \omega_m} \tag{2}$$

where $\mathrm{p_p}$ is the pump outlet pressure (Pa), $\mathrm{Q_p}$ is the pump flow rate (m³/s), $\mathrm{T_m}$ is the motor output torque (N·m), and $\mathrm{\omega_m}$ is the motor angular speed (rad/s).

The overall system efficiency is therefore:

$$\eta_{sys}=\frac{P_L}{P_p}=\frac{(T_m\cdot\omega_m)}{p_p\cdot Q_p} \tag{3}$$

As illustrated in Fig.3, the energy efficiency characteristics under low-speed, high-torque conditions differ markedly from those observed at moderate operating regimes.

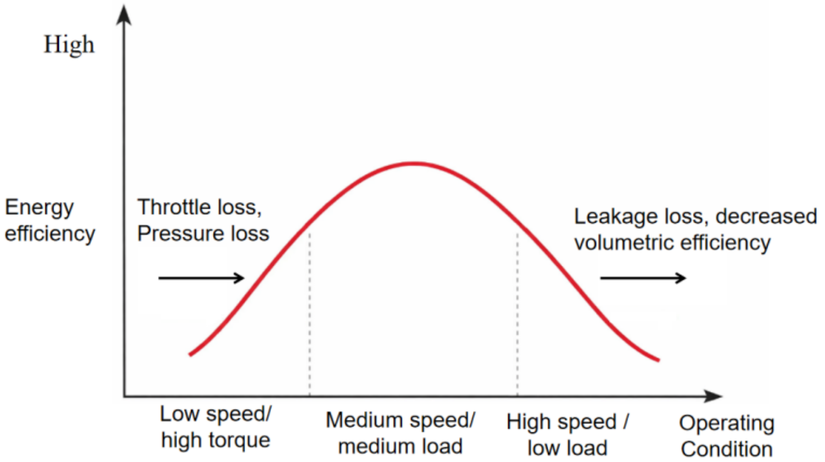

Fig. 3 -Schematic illustration of the qualitative variation in hydraulic system energy utilization efficiency under different operating conditions

Further, the difference between pump power and effective load power can be treated as the system loss power:

$$P_{loss}=P_p-P_L=P_{th}+P_v+p_m \tag{4}$$

where P_{th} is the throttling/relief loss, P_v is the volumetric loss, and P_m is the mechanical loss. For valve-throttling–dominated circuits, the throttling loss can be approximated as:

$$P_{th}\approx\Delta p_v\cdot Q_v \tag{5}$$

where Δp_v is the valve pressure drop (Pa) and Q_v is the valve flow rate (m³/s). Under low-speed high-torque operation, the system often operates in a low-flow/high-pressure-drop regime (small Q but large Δp and pressure level), which increases the share of P_{th} in total losses. Meanwhile, higher pressure also aggravates internal leakage and friction, causing P_v and P_m to rise with pressure, thereby jointly reducing η_{sys}.

Under low-speed operation with throttling or overflow control, elevated system pressures intensify throttling and pipeline losses in hydraulic systems *(Liu et al., 2019; Gu et al., 2020)*. In tuber crop machinery, frequent load fluctuations and parallel operation of travelling and working systems further shift the pump–motor operating point away from its optimal efficiency region, exacerbating energy efficiency degradation *(Merritt, 1967; Ivantysyn and Ivantysynova, 2001)*. These efficiency losses originate from system-level operating conditions and control strategies rather than from individual components, indicating that static parameter matching is insufficient and that dynamic, load-responsive analysis is necessary.

Load Fluctuations in Working Operations and Dynamic Response of Hydraulic Systems

Beyond steady-state energy efficiency characteristics, tuber crop machinery frequently experiences pronounced load fluctuations during field operations, which place higher demands on the dynamic response capability of hydraulic systems. Variations in soil conditions, working depth, crop spatial distribution, and periodic bagging operations cause the loads acting on digging, conveying, and bagging components to exhibit strong randomness and time-varying behavior *(Yang et al., 2023).* These load fluctuations are transmitted through hydraulic actuation circuits to pumps and valves, inducing continuous pressure and flow oscillations that are closely related to the pressure–flow characteristics of spool valves and the load equivalence behavior of valve-controlled systems *(Mao et al., 2025; Zhu et al., 2025)*.

From a system-dynamics perspective, pressure fluctuations fundamentally arise from transient imbalance among supplied flow, demanded flow, and leakage flow. When a load disturbance alters the required actuator flow or the effective backpressure, pressure and flow will be redistributed in a transient manner if pump/valve regulation cannot compensate on the same time scale.

When the dynamic response of a hydraulic system is insufficient to track rapidly varying loads, non-ideal operating states such as pressure shocks, flow lag, and speed fluctuations may occur, as widely reported in systems subjected to impact or highly transient loads *(Liang, 2025; Zhao, 2025; Zhu et al., 2025)*. In tuber crop machinery, such dynamic instabilities not only degrade motion smoothness of travelling and working components but may also increase the risk of tuber mechanical damage through transient impacts and speed fluctuations, as evidenced by experimental studies and recent reviews *(Liu, 2021; Dai et al., 2025)*.

The dynamic response capability of hydraulic systems is governed by the combined effects of circuit configuration, valve control strategies, and system damping, which determine their ability to attenuate load disturbances *(Zhou et al., 2015)*. To express the above factors in analyzable variables, the pressure dynamics of a representative control volume can be described by a pressure–flow continuity equation:

$$\frac{dp}{dt} = \frac{\beta_e}{V_e} \cdot (Q_{in} - Q_{out} - Q_{leak}) \tag{6}$$

where p is the chamber pressure (Pa), β_e is the effective bulk modulus (Pa), V_e is the effective chamber volume (m³), Q_{in} and Q_{out} are the inflow/outflow rates (m³/s), and Q_{leak} is the leakage flow rate (m³/s). This relation indicates that a larger β_e or a smaller V_e implies higher "hydraulic stiffness," making pressure more sensitive to flow imbalance and thus more prone to pressure peaks under load transients; conversely, larger effective volume and compressibility effects introduce more pronounced dynamic lag.

Meanwhile, actuator speed fluctuations can be viewed as a mapping from flow disturbances to speed disturbances. For a hydraulic motor, for example:

$$\omega_m \approx (\eta_v \cdot Q_m)/D_m \tag{7}$$

where ω_m is the motor angular speed (rad/s), Q_m is the flow into the motor (m³/s), D_m is the motor displacement (m³/rad), and η_v is the volumetric efficiency. Therefore, when valve throttling or flow redistribution causes Q_m to fluctuate, speed oscillations emerge directly and may be transmitted through conveyors, sieving mechanisms, and other structures as impact loads.

Under parallel operation of multiple actuators, hydraulic coupling may further amplify load disturbances into system-level dynamic instability, making dynamic response a key constraint on operational stability and working quality of potato harvesting machinery and motivating further system-level investigation of multi-actuator coupling mechanisms.

Coupling Characteristics of Hydraulic Systems under Parallel Operation of Multiple Actuators

With increasing functional integration of tuber crop machinery, travelling systems and working units such as digging, conveying, separation, and bagging are often driven by a common hydraulic power source, making parallel multi-actuator operation a prevalent configuration.

Although individual actuators perform different functions, their power demands are coupled at the system level through the shared pump and hydraulic circuits, resulting in a multi-load coupled operating state, as schematically illustrated in Fig. 4.

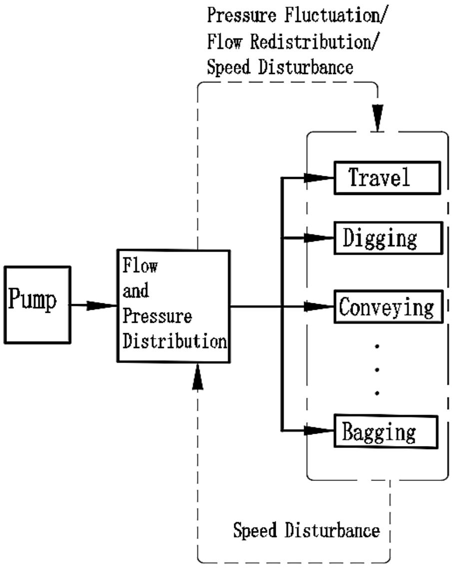

Fig. 4 -Schematic illustration of power coupling in a hydraulic system under parallel operation of multiple actuators

Variations in the load of one actuator may disturb the balance of flow and pressure distribution, and under limited regulation capability, lead to mutual interference among actuators, manifested as travelling speed fluctuations, unstable rotational speeds of working components, or delayed motion responses *(Jin et al., 2022)*. Moreover, such coupled operation may cause the hydraulic system to operate persistently away from its high-efficiency region, further deteriorating overall energy utilization efficiency. From a system-level shared-resource perspective, coupling arises directly from competition between pump supply capacity and branch demands. For a parallel system sharing a common pump source, the total supplied flow satisfies:

$$\mathrm{Q_p = \sum Q_I + Q_{leak}} \tag{8}$$

where $\mathrm{Q_p}$ is the pump flow rate, $\mathrm{Q_I}$ is the instantaneous flow demand of branch i (e.g., travel, digging, conveying), and Q_leak denotes leakage. When the load in one branch increases abruptly (e.g., higher digging resistance or an incipient conveyor jam) and raises its pressure requirement, system pressure and branch flows undergo dynamic redistribution if pump/valve regulation cannot increase supply or reallocate flow on the same time scale, thereby propagating a local disturbance into system-wide fluctuations.

Further, power coupling can be characterized by the relationship between pump power and branch power:

$$\mathrm{P_p = p_p \cdot Q_p \approx \sum(p_i \cdot Q_i) + P_{loss}} \tag{9}$$

where $\mathrm{p_i}$ is the pressure level in branch i, and $\mathrm{P_{loss}}$ represents loss-power terms such as throttling, leakage, and mechanical losses. This relation indicates that when $\mathrm{p_i}$ rises while $\mathrm{Q_i}$ is maintained or increased, a larger share of pump power is consumed by that branch, forcing other branches to experience flow reduction or pressure drop, which manifests as speed fluctuations and response lag.

During tuber crop harvesting, simultaneous load variations in travelling and working systems amplify coupling effects under parallel operation, increasing uncertainty in hydraulic system behavior. Especially in systems with multi-way valve distribution or load-sensing (LS) supply, the interplay between pressure-margin regulation and flow redistribution is inherently competitive. When multiple branches request flow simultaneously, priority and saturation effects may arise, allowing a disturbance in one branch to propagate to others as pressure or flow fluctuations and creating a cyclic amplification mechanism of “interaction-readjustment-reinteraction”. As traditional designs often neglect such coupling by treating actuators as independent loads, multi-actuator coupling has become a key system-level cause of energy efficiency degradation and dynamic instability in hydraulic systems of tuber crop machinery.

Constraints of Crop Damage Sensitivity on Drive Stability

Mechanical damage to tuber crops during harvesting is strongly associated with transient motion states of working components. Speed fluctuations, torque transients, and vibrations increase non-ideal crop–machine interactions, making drive system stability a critical boundary condition for crop quality rather than merely a mechanical performance metric *(Stropek et al., 2022)*. The damage risk induced by drive instability can be formulated as a measurable causal chain: speed disturbances Δv(t) and additional acceleration a(t) first alter the relative impact velocity and contact process, and then translate into bruising- and skin-damage outcomes through quantifiable metrics such as impact energy, peak contact force, and sliding friction work.

During tuber crop harvesting, operations such as digging, conveying, and separation are typically conducted under low-speed continuous conditions, placing higher stability requirements on drive system motion smoothness than those of general soil-working machinery. When load disturbances or circuit coupling induce pressure pulsations and flow fluctuations in hydraulic drives, the resulting transient velocity deviations and accelerations of working components act directly on tubers, increasing impact loads and relative sliding amplitudes *(Deng et al., 2022; Mohsenin et al., 1965)*. If the tuber–component contact is simplified as a transient impact with an effective mass $\mathrm{m_{eff}}$, the additional impact energy induced by speed fluctuations can be expressed as:

$$\mathrm{E_{imp}(t) = 0.5 \cdot m_{eff} \cdot [v_{rel}(t)]^2} \tag{10}$$

where $\mathrm{v_{rel}(t)}$ is the relative velocity between the tuber and the component. When drive instability causes $\mathrm{v_{rel}(t)}$ to increase abruptly, $\mathrm{E_{imp}(t)}$ rises quadratically, markedly elevating the risks of skin rupture and bruising. Further, the peak contact force can be approximated using an equivalent stiffness k_{eff} and the maximum contact deformation x_{max}:

$$F_{peak} \approx k_{eff} \cdot x_{max} \tag{11}$$

For abrasion/wear-type damage, the friction work associated with sliding contact can be used:

$$W_{fric} = \int \mu \cdot N(t)\dot{s}(t)dt$$

where μ is the friction coefficient, N(t) is the normal load, and $\dot{s}(t)$ is the relative sliding velocity. Speed fluctuations not only increase $v_{rel}(t)$ but may also enlarge the fluctuations of $\dot{s}(t)$ and N(t), thereby increasing W_{fric}.

The corresponding pathways linking drive system instability, component motion response, and tuber loading are summarized in Table 2. Such instability-induced mechanical actions are difficult to fully mitigate solely through structural compliance or material-based buffering.

Table 2

Conceptual correspondence between drive instability and the resulting load states of tubers

Drive system instability factor	Motion response of working components	Tuber loading and kinematic consequences	Damage risk manifestation
Pressure pulsation	Transient velocity fluctuation	Increased impact force peaks	Skin rupture, localized compression damage
Flow fluctuation	Abrupt acceleration variation	Increased relative displacement amplitude	Abrasion, epidermal wear
Multi-circuit coupling	Motion rhythm instability	Discontinuous contact processes	Aggravated cumulative damage
Load mutation	Short-term overload response	Stress concentration at contact interfaces	Internal tissue damage

Tuber damage during harvesting is more sensitive to dynamic fluctuations than to average operating parameters. In hydraulic drives, throttling regulation, limited damping, and delayed control response may induce short-term velocity disturbances, especially under low-speed, high-torque conditions. As a result, damage sensitivity shifts the evaluation of hydraulic drive systems from basic drivability toward a comprehensive requirement for high motion smoothness and low disturbance, providing a key motivation for subsequent optimization and control strategy development.

Summary

This chapter identifies energy efficiency degradation, limited dynamic response, multi-actuator coupling, and crop damage sensitivity as the dominant system-level constraints of hydraulic drive systems in tuber crop machinery. Low-speed, high-torque operation, stochastic load variations, and shared hydraulic power sources jointly drive systems away from high-efficiency regions and amplify dynamic instability, while crop sensitivity further imposes stringent requirements on drive smoothness and disturbance suppression.

These issues are inherently intertwined, forcing hydraulic drive systems in tuber crop machinery to address multi-objective trade-offs among energy efficiency, dynamic stability, and operational quality. Therefore, system-level investigation of structural design and control strategies is required to enable coordinated optimization under complex operating conditions.

RESEARCH PROGRESS ON OPTIMIZATION AND CONTROL TECHNOLOGIES FOR HYDRAULIC DRIVE SYSTEMS

The previous chapter identified the major challenges of hydraulic drive systems in tuber crop machinery under complex operating conditions, including energy utilization, dynamic response, multi-actuator coupling, and crop damage constraints. These challenges arise not from limitations of individual components but from the coupled effects of system structure, energy distribution, and dynamic control. Consequently, traditional design approaches based on static parameter matching or single performance metrics are insufficient to meet multi-condition operational demands. In response, recent studies have increasingly shifted toward system-level structural optimization and control strategy design to improve overall hydraulic system performance *(Tian et al., 2026; He et al., 2026)*.

Structural optimization improves energy transmission and system matching through configuration and integration, while control strategies enhance adaptability to load disturbances and operating condition variations. In tuber crop machinery, hydraulic drive systems must jointly meet requirements of traction, smoothness, energy efficiency, and crop damage mitigation. Accordingly, this chapter presents a classified and comparative review of recent structural optimization and control strategies for hydraulic drive systems under typical tuber crop harvesting conditions.

System Structural Optimization and Power Matching Methods

Recent studies have addressed energy efficiency and stability issues of hydraulic drive systems under low-speed, high-torque, and multi-condition operation through system structural optimization and power matching *(Man et al., 2025; Fan et al., 2025; He, 2025; Zhao et al., 2025)*. As a key link between pump, motor, and load, power matching determines long-term operation within high-efficiency regions. Typical matching relationships and their effects on energy efficiency are summarized in Table 3.

Table 3

Typical influencing factors of pump–motor–load power matching relationships in hydraulic drive systems

Matching Stage	Key Matching Factors	Mismatch Manifestations	Impact on Efficiency and Stability
Pump–load matching	Flow rate range and load variation amplitude	Frequent throttling or overflow	Reduced system efficiency and aggravated heat generation
Pump–motor matching	Displacement ratio and operating pressure range	High-pressure low-flow or low-pressure high-flow conditions	Narrowed high-efficiency operating region
Motor–load matching	Output speed and load resistance	Speed fluctuations or insufficient torque	Degraded drive stability
Overall system matching	Multi-condition coverage capability	Impact during operating condition switching	Reduced long-term operating efficiency

Numerous studies have demonstrated that improper pump–motor parameter matching causes hydraulic drive systems to deviate from their optimal efficiency regions under typical operating conditions, resulting in increased energy loss and temperature rise *(Chen et al., 2025; Sun et al., 2025)*. At the parameter selection level, research primarily focuses on rated pressure, displacement, and speed range of pumps and motors to ensure adequate power reserve and efficiency margins. Combined pump–motor efficiency models have been employed to compare energy utilization characteristics of different displacement combinations and identify favorable matching schemes *(Ge et al., 2019)*. For instance, a study on a crawler-type self-propelled harvester showed that optimizing pump displacement and travel motor specifications shifted dominant operating points toward medium-to-high efficiency regions, significantly reducing fuel consumption and system temperature rise *(Qu et al., 2025)*, as illustrated in Fig. 5. “Efficiency-island clustering” is usually derived under fixed speed–temperature–pressure conditions. In field operation, temperature-driven viscosity changes increase leakage and shift the efficiency map, so the same operating point may yield different efficiencies—hence power matching must be considered together with thermal management and oil-condition effects.

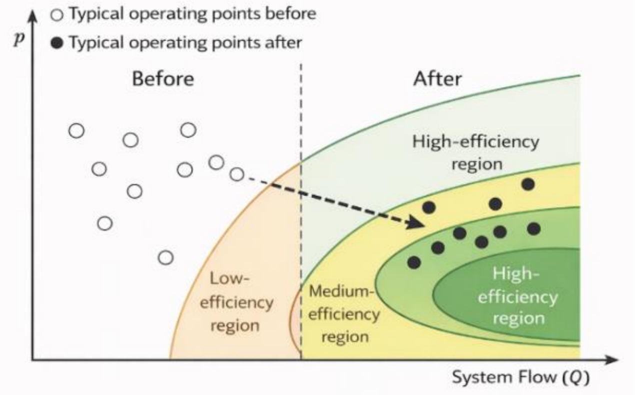

Fig. 5 -Distribution of typical operating points within the efficiency map before and after pump–motor parameter matching optimization

In addition to parameter matching, system structural configuration strongly influences power transmission and energy loss. Simplification of circuits and reduction of throttling and overflow links can mitigate efficiency degradation under low-speed, high-torque conditions. However, under rapidly varying loads or parallel multi-actuator operation, structural and parameter-level optimization alone cannot suppress dynamic fluctuations, necessitating the introduction of control strategies. This implies that power matching is shifting from a purely static design task to a design–control co-optimization problem: on top of sound hardware sizing, online control must compensate load disturbances and mode transitions to keep operating points within an efficient and stable feasible region.

Application of Load-Sensing and Electro-Hydraulic Control Technologies

Because tuber crop machinery operates predominantly under time-varying loads, the dynamic performance of hydraulic drive systems is highly dependent on control strategy design. Load-sensing control, which adapts power supply to load variations, has therefore become a central research direction for improving hydraulic system performance under complex operating conditions.

Load-sensing (LS) control adjusts pump output according to actuator load pressure by maintaining an approximately constant pressure margin Δp between pump outlet and load pressure (Fig. 6), thereby reducing throttling losses and improving partial-load efficiency. In agricultural machinery, LS systems are widely used to stabilize travelling speed under fluctuating resistance by enabling pump output to adapt to load demand *(Chen Suiying et al., 2017)*. However, under parallel multi-actuator operation or rapid load variations, pressure signal lag and circuit coupling may still induce oscillations or response delays, limiting LS performance in complex hydraulic systems *(Xu & Cheng, 2018).*

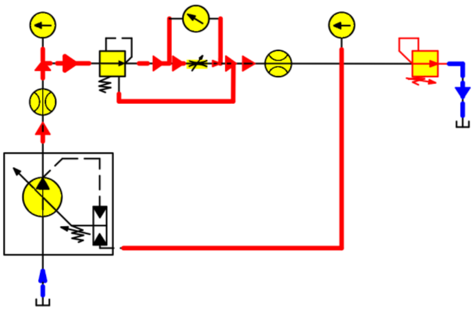

Fig. 6 -Schematic diagram of the Δp control principle of a load-sensing (LS) hydraulic system

Electro-hydraulic proportional and closed-loop control technologies have been introduced to improve hydraulic system adaptability under complex operating conditions. By enabling continuous regulation of flow, pressure, and speed, such approaches support multivariable closed-loop control and enhance disturbance rejection, as demonstrated by electronic load-sensing schemes such as MELS *(Cheng et al., 2023)* and closed-loop speed or pressure control applications *(Duan et al., 2024)*.

Although load-sensing and electro-hydraulic control improve adaptability and stability, single-variable strategies cannot adequately coordinate parallel multi-actuator systems, making coordinated control and energy management indispensable.

Multi-Actuator Coordinated Control and Energy Management

With increasing functional integration of tuber crop machinery, parallel multi-actuator operation has become the prevailing mode of hydraulic drive systems. Under this configuration, travelling, digging, conveying, separation, and bulk-handling units often operate simultaneously while sharing a common hydraulic power source, resulting in pronounced multi-load coupling. Consequently, control strategies designed for single circuits or individual actuators are generally inadequate to ensure rational power distribution and consistent dynamic response at the system level. A shared pump and valve distribution couple branch flows and pressures, so single-loop “local optimum” actions can propagate into system-level interactions that degrade both efficiency and stability.

Multi-actuator coordinated control addresses system-level coupling by scheduling power and flow distribution among actuators according to priority, preventing local load disturbances from escalating into global performance fluctuations (Fig.7).

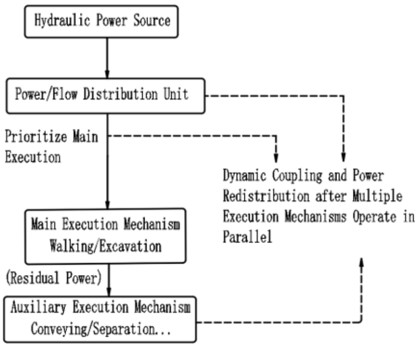

Fig. 7 - Schematic diagram of power priority allocation and coordinated control in a hydraulic system under multi-actuator parallel operating conditions

Typical implementations include priority-based allocation, master–slave schemes, and hierarchical control architectures. From a comparability standpoint, these strategies represent different ways of handling resource competition: priority allocation protects key branches under limited supply but sacrifices non-priority performance; master–slave control improves dynamic consistency for critical tasks but is more sensitive to modeling/parameter errors and synchronization; hierarchical control enhances robustness via supervisory scheduling with lower-level loops, at the cost of richer sensing and higher control bandwidth.

In multi-actuator systems, coordinated control has further evolved into an energy management problem, shifting the focus from individual task performance to system-level energy efficiency and dynamic stability. Energy management aims to rationally allocate and temporally coordinate actuator power demands under limited power supply, thereby reducing peak loads and smoothing system fluctuations. Representative studies have introduced accumulators or energy buffering units to enable peak shaving and impact suppression during coordinated multi-actuator operation, resulting in improved overall operational smoothness *(Xu et al., 2025; Sun et al., 2024)*. Notably, accumulator benefits are bounded by charge–discharge frequency, available pressure margin, and sizing; if disturbance frequencies exceed its effective response range or the supply remains at high pressure/temperature, peak-shaving may not be sustained and additional control coupling and safety constraints (pressure limits, relief, fault-degradation logic) may be introduced.

Although coordinated control and energy management improve stability and efficiency of multi-actuator hydraulic systems, their complexity limits practical application in agricultural machinery, making reliability-oriented intelligent and information-fusion-based approaches an emerging research focus.

Application Progress of Intelligent and Information Fusion Control Technologies

As agricultural operating conditions become increasingly complex, fixed-parameter or local-feedback hydraulic control is inadequate to meet stability and energy efficiency requirements under rapid load fluctuations and mode switching. Information-fusion-based intelligent control, which integrates multi-source signals to enhance system state awareness, therefore provides a more robust basis for decision-making and control under highly variable operating conditions. More specifically, fusion outputs are typically cast as state variables (e.g., load level, fluctuation intensity, terrain state, operating mode) to trigger pump-displacement adjustment, valve-opening reallocation, or drive-mode switching, thereby integrating efficiency, bandwidth, and coupling constraints within a single decision framework.

At the implementation level, information fusion has been incorporated into electro-hydraulic proportional control and closed-loop speed regulation to dynamically adjust pump–motor operating points, thereby improving dynamic response and energy utilization efficiency under low-speed, high-torque conditions *(Cheng et al., 2018; Yu et al., 2024)*. By how control logic is generated, intelligent control can be grouped into three types: rule-/state-logic (simple and explainable for mode scheduling and resource competition), model-based (optimizes pump/valve actions under dynamics and loss constraints but is model/parameter sensitive), and data-driven (learns mappings from data for nonlinear adaptation yet requires strict validation of generalization, interpretability, and safety bounds). Meanwhile, advances in embedded computing and communication technologies have enabled the application of intelligent control methods based on rule logic, state criteria, or data-driven models to assist parameter tuning and operating mode selection in hydraulic drive systems. However, current applications in agricultural hydraulic systems remain largely focused on state identification and decision support, while real-time performance, reliability, and interpretability under strongly nonlinear and highly uncertain operating conditions still lack sufficient engineering validation. Limitations typically stem from harsh-field sensing (mud/water, vibration, EMI), delay- and cycle-limited closed-loop bandwidth, and insufficient stability and safe-degradation logic under jams, impact loads, and multi-branch saturation.

Overall, intelligent and information fusion control offers new possibilities for hydraulic system optimization under complex conditions, but its practical deployment must reconcile system structure, operating-object sensitivity, and control stability. Under tuber damage sensitivity constraints, practical progress lies less in ever more complex algorithms than in explainable state criteria, clear mode-switching logic, and robust safe-degradation strategies, so information fusion truly supports system-level co-optimization of efficiency–dynamics-coupling.

DEVELOPMENT TRENDS AND RESEARCH PROSPECTS

Based on current research and technological progress, this paper summarizes system-level development trends of hydraulic technologies in tuber crop mechanization, emphasizing that these trends represent logical extrapolations from existing research and engineering challenges rather than subjective forecasts.

(1) High-Efficiency and Low-Energy-Consumption Hydraulic System Design for Low-Speed, High-Torque Operating Conditions. Operation of tuber crop machinery under low-speed, high-torque conditions does not necessarily ensure high energy efficiency; instead, throttling losses and amplified pressure differentials may increase system energy consumption. Therefore, future hydraulic system design should shift from satisfying extreme operating capability toward system-level energy efficiency optimization under typical operating conditions, emphasizing coordinated trade-offs among power matching, energy transmission paths, and operating region selection.

(2) Coordinated Optimization Requirements of Driving Stability and Crop Damage Sensitivity. Tuber crops are highly sensitive to mechanical impacts and speed fluctuations, linking drive system stability directly to operation quality and crop damage. Although existing studies often treat driving stability and crop damage separately, they are tightly coupled in field operations through speed fluctuations and impact loads. Therefore, future research should integrate both aspects into a unified analytical framework and pursue system-level coordinated optimization.

(3) Coordinated Control and Energy Management of Multi-Actuator Hydraulic Systems. With the increasing integration of operational functions, parallel operation of multiple actuators has become the normal operating condition of hydraulic systems in tuber crop machinery. Under such conditions, control strategies oriented toward local circuits or individual actuators are difficult to ensure the rationality of overall power distribution and the consistency of system dynamic response. It can therefore be concluded that coordinated control and energy management for multi-actuator systems will become an important research direction in the development of hydraulic systems, with the objective of coordinating energy supply and dynamic response from a system-level perspective.

(4) Engineering-Oriented Intelligent and Information Fusion Control. The application of intelligent and information fusion control technologies in hydraulic systems is mainly concentrated at the levels of state identification and decision support. In agricultural hydraulic systems, the value of intelligent technologies is more reflected in enhancing adaptability to complex operating conditions rather than replacing traditional control structures. Therefore, future research on intelligent control should take engineering feasibility as a prerequisite and evolve in coordination with hydraulic system structural characteristics and control stability.

(5) Necessity of Coordinated Advancement between Theoretical Research and Engineering Practice. The review results indicate that some theoretical models and control methods for hydraulic systems still suffer from insufficient engineering applicability under complex field operating conditions. Future research should establish a tighter closed-loop relationship among model development, control design, and long-term operating condition validation, so as to enhance the engineering applicability of research outcomes.

Overall, the development trends of hydraulic technologies in the mechanized production of tuber crops are characterized by a gradual evolution from local optimization toward system-level coordination, from single performance metrics toward multi-objective comprehensive constraints, and from experience-oriented approaches toward engineering validation-oriented development.

CONCLUSIONS

The key contradiction of hydraulic systems in tuber crop machinery does not lie in whether sufficient power can be provided, but in the difficulty of simultaneously achieving on-demand energy supply and stable output under multiple operating conditions. Under low-speed, high-torque conditions, the energy consumption mechanisms caused by throttling losses and amplified pressure differentials, the dynamic fluctuations induced by operating condition switching, and the coupling effects resulting from multiple actuators sharing a common power source jointly constitute the main constraint chain on system energy efficiency and operational smoothness. Existing studies have established relatively clear technical frameworks in terms of structural optimization and power matching, load-sensing and electro-hydraulic control, as well as coordinated control and energy management; however, their effectiveness is often constrained by uncertain field loads and the boundaries of engineering implementation.

Therefore, future research oriented toward engineering applications should shift from “locally improving individual performance indicators” to “system-level multi-objective coordination,” incorporating energy efficiency, stability, and crop damage sensitivity into a unified design–control closed-loop framework.

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