RESEARCH PROGRESS AND DEVELOPMENT TRENDS OF KEY TECHNOLOGIES FOR ELECTRIC TRACTORS

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纯电动拖拉机关键技术研究进展与发展趋势

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ABSTRACT
Research on electric tractors has expanded rapidly; however, previous reviews have generally examined energy sources, powertrains, intelligent control, and supporting infrastructure separately. This narrative review establishes an integrated technology-chain framework encompassing energy supply, electric drive systems, energy management, power take-off (PTO) and hitch control, autonomous operation, simulation, standardization, and industrial deployment. The available evidence was synthesized and compared in terms of system performance, advantages, limitations, and technological maturity. The results indicate that battery-electric systems can reduce energy consumption and life-cycle environmental impacts but remain constrained by limited operating endurance, high battery costs, thermal-safety risks, and insufficient charging capacity. Hybrid and fuel-cell powertrains offer greater adaptability to varying operating conditions but introduce additional system complexity. Future research should prioritize standardized duty cycles, integrated simulation frameworks, modular energy-replenishment systems, reliability testing, and interoperability standards.

摘要
电动拖拉机研究发展迅速，但既有综述通常将能源来源、动力系统、智能控制和配套基础设施割裂讨论。本研究采用叙述性综述方法，建立了涵盖能源供给、电力驱动、能量管理、动力输出轴与悬挂控制、自主作业、系统仿真、标准体系及产业化应用的技术链框架，并从性能、优势、局限和成熟度等方面比较相关证据。结果表明，纯电动系统能够降低能源需求和全生命周期环境影响，但仍受续航能力、电池成本、热安全与充电能力制约；混合动力和燃料电池路线可提高工况适应性，却增加系统复杂性。未来应重点推进标准化作业循环、集成仿真、模块化能源补给、可靠性测试及互操作标准。

INTRODUCTION
Agricultural tractors must deliver high tractive power and power take-off (PTO) output under strongly variable loads, while reducing fossil-fuel use, local air pollutants, and greenhouse-gas emissions. Electric powertrains offer high conversion efficiency and precise torque control, but their benefits depend on the electricity mix, battery manufacture, duty cycle, and charging strategy. Life-cycle studies have reported substantial reductions in climate and resource impacts for battery-electric field systems, while also identifying battery production, purchase cost, mass, and operating range as important trade-offs *(Lagnelöv et al., 2021; Mousazadeh et al., 2011; Vogt et al., 2021)*.

This review used a structured narrative-synthesis protocol. Peer-reviewed English- and Chinese-language studies were identified in Web of Science Core Collection, Scopus, and CNKI using terms related to electric and hybrid tractors, batteries, electric drives, energy management, PTO/hitch control, autonomous navigation, and simulation. Searches prioritized 2015-2026 publications; earlier landmark prototypes, control methods, and life-cycle assessments were retained, and backward citation searching supplemented the results.

Studies were included when they addressed tractor-specific architecture, components, modeling, control, field testing, environmental performance, or deployment economics and supplied sufficient evidence for comparison. Because tasks, power classes, and metrics were heterogeneous, the evidence was grouped by technology chain and compared using reported indicators, advantages, limitations, and maturity rather than pooled statistically.

Unlike previous reviews focusing on individual subsystems or the status of domestic technological development *(Liu et al., 2022; Liu H.L. et al., 2024; Wang L. et al., 2025)*, this study links component-level advances to whole-vehicle integration and deployment readiness. It compares powertrain architectures; evaluates batteries, electric drives, energy management, PTO and hitch control, autonomous navigation, and simulation methods; and identifies cross-cutting bottlenecks to establish a staged research agenda. The proposed framework distinguishes laboratory-scale advances from field-ready capabilities.

Table 1

Literature retrieval and screening framework

Review stage	Database / source	Search topic	Selection criteria	Analytical use
Database retrieval	Web of Science Core Collection; Scopus; CNKI	Electric and hybrid tractors; batteries; electric drives; energy management; PTO/hitch control; autonomous navigation; simulation	Peer-reviewed English- or Chinese-language studies; priority period 2015–2026	Identify tractor-specific technical, environmental, and deployment evidence
Supplementary retrieval	Backward citation searching	Landmark prototypes, control methods, and life-cycle assessments	Earlier studies retained only when foundational to technological evolution	Trace development stages and preserve seminal evidence
Eligibility screening	Title, abstract, and full-text review	Architecture, components, modeling, control, field testing, environmental performance, and economics	Tractor-specific scope and sufficient quantitative or qualitative evidence for comparison	Exclude non-tractor studies and records with insufficient comparative evidence
Evidence synthesis	Included studies	Reported performance, advantages, limitations, and indicative maturity	Grouped by technology chain; no statistical pooling because tasks and metrics were heterogeneous	Support comparative tables, bottleneck analysis, and the staged research agenda

Although electric tractors have achieved notable advances in diversified power supply and intelligent control, they still face practical challenges in operational adaptability, high manufacturing costs, and large-scale industrial promotion. Focusing on key common technologies, core industry bottlenecks, and actual agricultural production needs, this study aims to advance the industrialization and practical application of electric tractors. The main research contents are as follows.

(1) Development overview: The technological evolution of electric tractors is reviewed across three generations, with emphasis on their technical configurations, characteristics, and limitations. Domestic and international development models are compared, and diversified powertrain and energy-supply technologies, including hybrid and solar-energy systems, are evaluated. This analysis clarifies the evolution of electric tractor technologies and provides a basis for improving operating endurance and adaptability to different applications, thereby supporting a differentiated development strategy for China's electric tractor industry.

(2) Core power technologies: Optimization strategies and technological advances in traction batteries, electric drive systems, energy management, and power coordination are examined to establish an integrated pathway for powertrain development.

(3) Intelligent control: Electric power steering, active suspension, autonomous navigation, and system simulation are reviewed to improve adaptability to field conditions and operational performance.

(4) Standard system and industrialization: Bottlenecks related to technologies, key components, standards, and supporting infrastructure are identified, and pathways toward industrialization are proposed to facilitate large-scale adoption.

Overall, this review supports technological innovation and industrial upgrading in the electric tractor sector, thereby contributing to the mechanized, intelligent, and environmentally sustainable development of agriculture in China.

TECHNOLOGICAL EVOLUTION AND POWER-SUPPLY CONFIGURATIONS

Development history and representative tractor models

The development of electric tractors falls into three stages. From the early 20th century to the 1970s was the wired power supply stage: Harbin Songjiang Tractor Factory developed China's first "Dianiu 28" electric tractor, powered by transmission lines with a 28 kW rated output, pioneering domestic research *(Yu et al., 2024a)* but not widely used due to grid limitations. From the 1970s to the early 21st century, it shifted from wired power to on-board batteries, enabling wheel driving and power take-off shaft control, with initial promotion driven by energy storage technology. Since the early 21st century, high-density battery technology has supported long-time light-load operation; intelligent functions and unmanned driving based on path planning have matured. Electric tractors covering a wide range of power ratings are currently being developed by numerous manufacturers *(Han, 2023)*.

International research has progressed from solar-assisted and battery-powered prototypes to autonomous platforms, hybrid powertrains, and farm-level energy planning. In addition to the life-cycle and farm-system analyses summarized above, prototype- and system-level studies have investigated tractor electrification, autonomous field robots, parallel-hybrid control strategies, hardware-in-the-loop validation, and series-hybrid powertrain sizing *(Dalboni et al., 2019; Estevez et al., 2024; Ghobadpour et al., 2021; Ghobadpour et al., 2022; Grimstad and From, 2017; Mocera and Somà, 2020; Mocera, 2021; Pedersen et al., 2006; Rosales et al., 2022; Ueka et al., 2013)*. Collectively, these studies demonstrate the technical feasibility of electric agricultural machinery; however, operating endurance under field conditions, implement integration, charging logistics, and economic viability remain dependent on the specific application.

Research and product development in China have pursued battery-electric, diesel-electric hybrid, and hydrogen fuel-cell technologies in parallel. High-power hybrid prototypes have focused on sustained operation under heavy loads, whereas smaller battery-electric tractors have been developed primarily for greenhouse, orchard, and transport applications. Representative projects have advanced dual-motor power coupling, electronically controlled continuously variable transmissions, distributed drive systems, and tractor-specific energy-management strategies *(Feng et al., 2023; Li et al., 2023; Wen et al., 2025)*. A major advantage is the ability to leverage the existing agricultural-machinery supply chain for rapid technological development. However, validation across diverse operating conditions remains limited, some high-end components still depend on imports, and charging and maintenance infrastructure is unevenly developed. Representative products are presented in Fig. 1.

(a) X-Tractor *(b) CNH concept tractor* *(c) MK-V* *(d) E-Power*

(e) HB2204 *(f) E3404-8H* *(g) ET14100* *(h) E904i*

Fig. 1 - Representative electric tractor models developed in China and other countries

The comparison indicates that powertrain selection depends primarily on the duty cycle rather than following a uniform geographical pattern. Battery-electric systems are the most technologically mature option for low- and medium-power tasks with predictable daily energy requirements. Hybrid systems retain an advantage in prolonged, high-load operations, whereas hydrogen fuel-cell systems remain at the prototype or early demonstration stage because their potential vehicle-level benefits must be weighed against the challenges associated with hydrogen production, storage, and distribution.

Accordingly, Table 2 compares representative tractor platforms in terms of powertrain type, reported performance, advantages, limitations, and suitable applications.

Table 2

Representative electric tractor platforms and their application characteristics

Representative platform	Power train or energy-supply type	Reported performance	Main advantage	Main limitation	Suitable application	Technology maturity
Dianiu 28 *(Yu et al., 2024a)*	Cable-powered electric	Rated power: 28 kW	Continuous power supply	Grid and cable restriction	Fixed-area work	Historical prototype
Solar-assisted prototype *(Mousazadeh et al., 2011)*	Solar-assisted battery-electric	≈14 t CO_2-eq annual reduction in case study	Lower life-cycle impact	Cost, mass and range	Light duty / demonstration	Prototype
Unmanned platform *(Chen et al., 2022)*	Battery electric; dual motor	2 × 7.5 kW; ≥3.5 h	Compact autonomous operation	Low power and endurance	Orchards / protected farming	Field prototype
Autonomous fleet *(Lagnelöv et al., 2021)*	Battery-electric fleet	102 vs 293 kg CO_2-eq ha^{-1} y^{-1}	Life-cycle benefit	Charging coordination	Predictable field schedules	System simulation / pilot evidence
Terrain-aware platform *(Luo et al., 2024)*	Battery electric	Speed stability +45.09%; energy −9.51%	Terrain adaptation	Single test setting	Variable-soil traction	Field prototype
Field charging / exchange *(Wallander et al., 2025)*	Battery-electric farm system	Process time +5%; energy 37.5% of diesel	Near-diesel work rate	Grid and logistics sensitivity	Large coordinated farms	Farm-system modeling

Comparative assessment of diversified powertrain technologies

Electric tractor development in China currently integrates diverse powertrain and energy-supply technologies, including battery-electric, diesel-electric hybrid, biomass-based, solar-powered, and fuel-cell systems. These technologies are being explored to overcome the limitations of battery-electric tractors in terms of operating endurance and adaptability to different applications, and substantial progress has been achieved. However, the available technological options differ considerably in power performance, economic viability, environmental adaptability, and technological and industrial maturity.

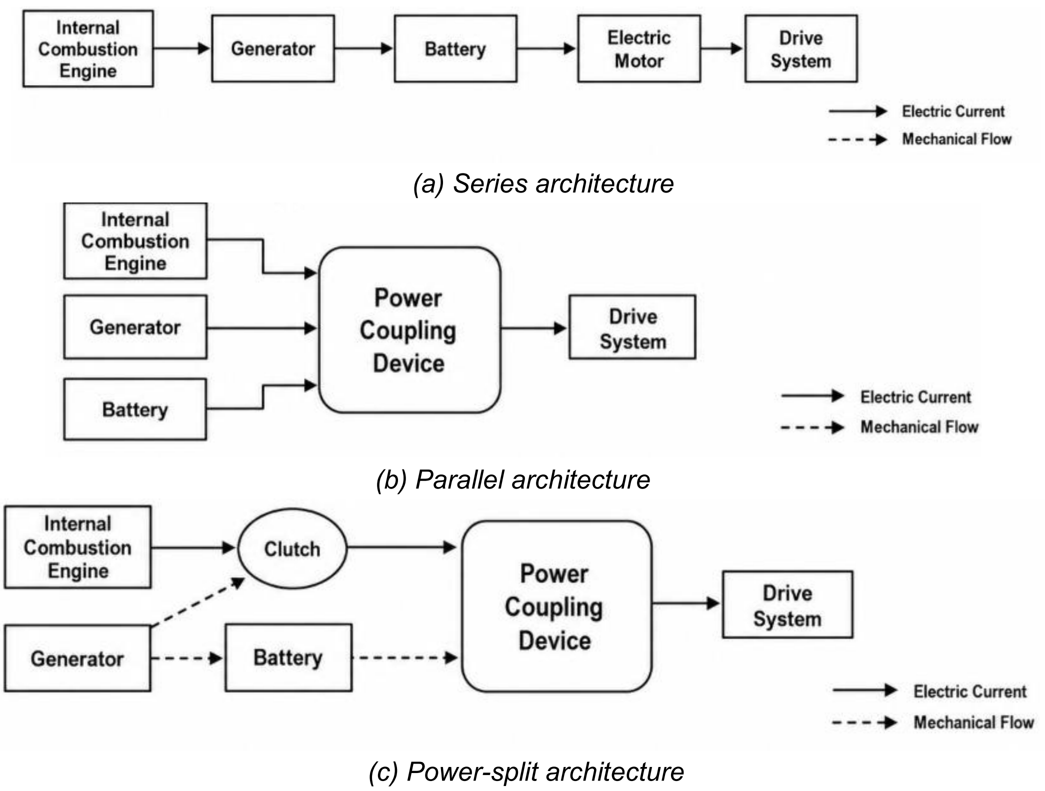

Fig. 2 - Architectures of hybrid electric powertrains

Diesel-electric hybrid systems can reduce engine transients and extend endurance while retaining rapid refueling. Series architectures simplify mechanical transmission and permit flexible engine operation; parallel and power-split layouts can achieve higher peak efficiency but require more complex coordination. Recent studies have used life-cycle-cost analysis, dynamic programming, model-predictive control, fuzzy following control, and hardware-in-the-loop testing to compare architectures and operating strategies *(Beligoj et al., 2022; Mocera, 2021; Zhang et al., 2023; Yan et al., 2024; Zhao et al., 2024a, 2024b; Pascuzzi et al., 2024)*.

The evidence is promising but remains dominated by prototypes, simulations, or individual duty cycles rather than multi-season commercial operation.

Solar energy is more viable as an auxiliary or farm-level energy source than as the sole source of traction power. Vehicle-mounted photovoltaic panels can supply low-power auxiliary systems and extend operating time, whereas rooftop or field-edge photovoltaic installations can provide electricity for battery charging or swapping stations. A solar-assisted plug-in hybrid tractor prototype achieved lower annual life-cycle emissions but remained constrained by battery weight and limited operating range *(Mousazadeh et al., 2011)*. Farm-system simulations further indicate that coordinated charging and battery swapping can maintain operational work rates while reducing energy consumption *(Wallander et al., 2025)*. Table 3 summarizes the advantages, limitations, and technological maturity of these solar-energy integration configurations.

Table 3

Comparison and technological maturity of solar-energy integration configurations

Integration configuration	Energy-system configuration	Reported performance	Main advantage	Main limitation	Technology maturity
Vehicle-mounted PV	PV + traction battery	Contribution to auxiliary power; tractor-specific field data remain limited	Utilizes otherwise unused vehicle surfaces	Area, shading, dust and mass	Concept / prototype
Solar-powered charging station	PV + stationary storage + charger	Output depends on solar irradiance and the sizing of the storage and charging systems	Separates solar-energy collection from the vehicle's available surface area	Land requirements and capital costs	Pilot / early deployment
Integrated farm-energy system	PV + grid + storage + fleet scheduling	Operational work rate depends on grid capacity, battery size, and logistical coordination	Supports multiple machines and peak-load management	Complex planning and seasonal use	System modeling / pilot

Biomass-derived fuels can utilize locally available agricultural residues and may reduce net fossil-carbon consumption. However, their relevance to electric tractors lies primarily in range-extender generators, farm microgrids, and hydrogen production rather than in the direct replacement of traction batteries. Studies of biodiesel, biomass gasification, and integrated biomass–solar systems have demonstrated the potential of locally sourced energy supplies *(Jing et al., 2025; Liu H., 2024; Sun et al., 2025; Wang D.G. et al., 2024)*. Nevertheless, feedstock logistics, gas-cleaning requirements, conversion efficiency, and seasonal feedstock availability limit their broader applicability. These technologies should therefore be evaluated at the farm-system level through comprehensive energy, emissions, and cost assessments.

Fuel-cell electric tractors offer fast refueling and high gravimetric energy density, but stack durability, hydrogen storage, thermal management, and fuel infrastructure remain decisive.

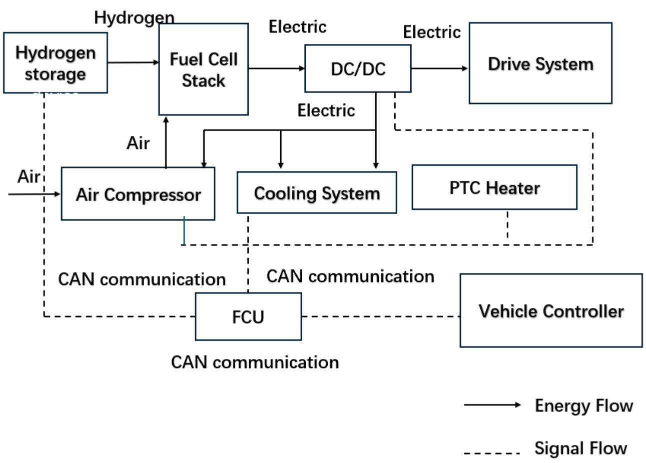

Fig. 3 - Fuel-cell electric tractor system architecture

Integrated electromechanical-hydraulic modeling has shown that optimized energy management can reduce hydrogen consumption and state-of-charge fluctuation under plowing and transport cycles *(Liu et al., 2023; Yu et al., 2024c; Zhang M. et al., 2025)*. Predictive control validated on a fuel-cell powertrain testbed also reduced damaging load cycling without sacrificing efficiency across three agricultural duty cycles *(Varlese et al., 2024)*. These results move the technology beyond concept analysis, but whole-tractor durability and farm-scale hydrogen supply still require field demonstration.

POWERTRAIN AND ENERGY MANAGEMENT TECHNOLOGIES

Battery systems and management

The power battery determines vehicle mass, available power, continuous operating time, thermal risk, and total cost. Lead-acid and nickel-metal hydride batteries retain niche advantages in cost or robustness, but lithium-ion chemistries dominate new electric-tractor designs because of their higher specific energy and cycle efficiency. Lithium iron phosphate prioritizes thermal stability and cycle life, whereas nickel-rich chemistries prioritize gravimetric energy density. Fig. 4 compares the principal performance trade-offs; the appropriate chemistry must be selected using task-level energy and peak-power demand, ambient temperature, packaging, and maintenance constraints rather than energy density alone.

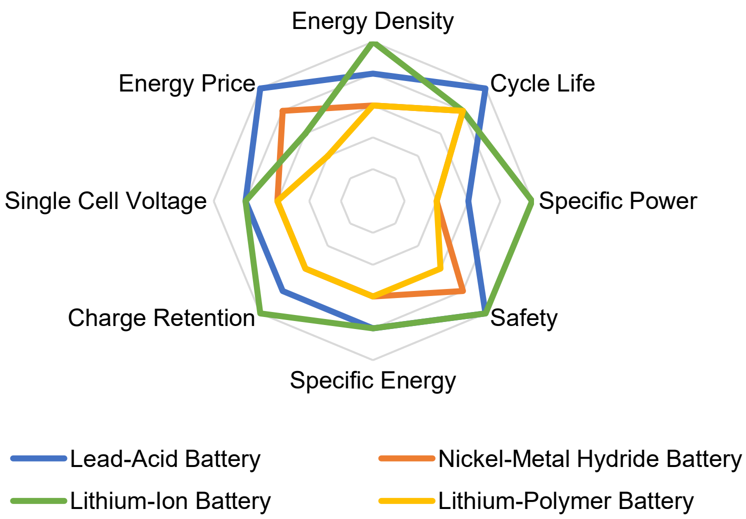

Fig. 4 - Comparison of battery technologies

Lithium-ion systems remain the practical baseline for current electric tractors. LFP cells are attractive for heavy-duty and harsh-environment applications because safety and cycle life are prioritized, while higher-energy chemistries can reduce pack mass for orchard, horticultural, and transport tasks. Battery sizing should also account for auxiliary hydraulic and PTO loads, which are often underrepresented when capacity is derived only from traction demand. Research on high-specific-energy systems and lithium-sulfur batteries indicates potential for future mass reduction, but field durability, cost, and safety validation remain incomplete *(Zhang et al., 2014; Wen et al., 2025)*.

Solid-state and sodium-ion batteries may eventually widen the feasible operating-temperature and cost envelope, but published tractor-specific evidence remains limited. Claims based on cell-level energy density cannot be transferred directly to pack or vehicle performance because structural protection, thermal management, state estimation, and power electronics add mass and losses. A defensible technology comparison therefore requires pack-level specific energy, usable depth of discharge, cycle life under pulsating loads, safety testing, and end-of-life recovery.

A tractor battery-management system must estimate state of charge and health, supervise voltage and temperature, balance cells, and enforce charge-discharge limits under rapidly changing traction, hydraulic, and PTO loads. The central challenge is not monitoring alone but reliable state estimation when current profiles, temperature, aging, and vibration differ markedly from standard road-vehicle cycles. Magneto-thermal coupling models have also been used to characterize battery temperature fields under dynamic loads *(Yang J.Q. et al., 2023)*.

Recent studies have combined filtering, power-frequency decomposition, condition recognition, and communication-network design to reduce battery peaks and improve energy allocation *(Xu et al., 2025; Xue et al., 2023; Zhang Q.H. et al., 2025)*. Data-driven estimators and digital twins can improve prediction, but they require representative field data, uncertainty bounds, and fail-safe behavior. Future validation should therefore report estimation error, computational load, aging sensitivity, and performance across multiple agricultural operations rather than a single simulated cycle.

Electric-drive architectures and control

Centralized drives preserve a conventional transmission path and therefore offer lower redesign cost, mature sealing and cooling, and straightforward maintenance. Their disadvantages are mechanical losses, limited independent wheel control, and reduced packaging flexibility. Distributed or wheel-side drives shorten the transmission path and enable independent torque allocation, but increase unsprung mass, sealing and thermal-management demands, controller coordination, and exposure to impact and mud.

For medium- and high-power tractors, dual-motor coupling provides an intermediate powertrain configuration that shifts motor operating points toward high-efficiency regions while maintaining mechanical robustness. Studies on the optimization of distributed-drive and coupled-drive systems have reported improvements in transmission efficiency and coverage of the operating range *(Li et al., 2023; Li et al., 2022)*. However, these comparisons are often based on different operating tasks and boundary conditions; therefore, the reported percentage improvements should not be considered directly transferable across systems or applications.

Motor selection must be matched to the actual low-speed, high-torque duty distribution. *Kwon et al. (2024)* found up to 7.9% difference in plowing energy consumption among motors with identical ratings but different efficiency-map distributions. This demonstrates that rated power alone is insufficient; frequent tasks, cooling limits, field-weakening operation, inverter losses, and gearbox ratios must be optimized jointly.

Distributed drive is therefore a promising architecture for precision traction and autonomous operation, but its present maturity is mainly prototype to early field-demonstration level. Centralized and coupled drives are more mature for near-term commercialization, especially where serviceability and component protection dominate the design decision.

Electric-drive control must maintain speed and traction while limiting wheel slip and energy loss under changing soil resistance. Rule-based and PID methods remain attractive for reliability and low computational demand, whereas fuzzy, observer-based, predictive, and learning-based controllers offer better adaptation at the cost of calibration, model, and validation burden.

Terrain-aware control provides a useful bridge between theoretical optimization and field operation. *Luo et al. (2024)* combined terrain-parameter identification, a sliding-mode observer, and optimal-slip control; hardware-in-the-loop and vehicle tests improved operating-speed stability by 45.09% and reduced total energy consumption by 9.51%. Other fuzzy and neural-network controllers have improved disturbance compensation, shift quality, and fault diagnosis *(Li Y. et al., 2024; Wang C.Y. et al., 2024; Yu et al., 2023; Yu et al., 2024b)*.

The main evidence gap is generalization. Many algorithms are evaluated on one soil, speed, implement, or simulated load. Future studies should disclose baseline controllers, sampling and computational requirements, uncertainty, and independent field validation across soil moisture, slopes, tire inflation, ballast, and PTO disturbances.

Hybrid power supply and energy management

A battery-supercapacitor hybrid energy-storage system separates energy demand from short-duration peak power. Passive topologies are simple but provide little control; semi-active topologies balance controllability, cost, and converter loss; fully active topologies provide the greatest power-allocation freedom but require two converters and more complex protection. Table 4 summarizes the functions, representative methods, benefits, limitations, and research priorities of key electric-tractor components and control systems.

Capacity sizing and control must be optimized together. Semi-active systems using fuzzy thresholds and genetic algorithms have reduced hourly power cost, while multi-objective allocation has reduced battery power fluctuation *(Li L.Q. et al., 2024a, 2024b; Xu et al., 2024)*. Deep-reinforcement-learning and predictive methods can further adapt power split to recognized agricultural conditions, but their robustness outside the training distribution remains a concern.

Table 4

Key electric-tractor components, control strategies, and research priorities

Component / strategy	Representative method	Reported indicator / advantage	Main limitation	Indicative maturity	Research priority
Battery and BMS	SOC/SOH estimation, balancing, thermal supervision	Reduces peak stress; safeguards usable energy	Aging, heat and limited field datasets	Commercial components; tractor validation developing	Pack-level safety and multi-season aging
Electric drive	Dual-motor coupling, terrain identification, slip control	Up to 7.9% motor-dependent plowing-energy difference; energy −9.51% in one terrain-aware test	Single-condition evidence and drivetrain complexity	Prototype to early field validation	Cross-soil and thermal validation
Hybrid storage	Semi-active DC/DC; fuzzy, optimization or predictive control	Buffers transient peak power and reduces battery fluctuation	Converter loss and sizing sensitivity	Laboratory / simulation to prototype	Joint sizing, aging and fault tolerance
PTO and hitch	Load following, force-position and fuzzy-PID control	Improves response and tillage-depth stability; metrics are not standardized	Impact loads and coupled dynamics	Prototype / subsystem field tests	Integrated standardized duty-cycle tests
Autonomous navigation	RTK-GNSS, sensor fusion, MPC and learning control	Centimeter-level guidance reported in controlled field studies	Perception uncertainty and functional safety	Field prototype; limited supervised deployment	Intervention, safety and energy metrics
Simulation / digital twin	Multi-domain models and HIL	Earlier controller verification and fault detection	Model fidelity and data interoperability	HIL established; digital twins emerging	Reusable models and parameter traceability

Semi-active topology is currently the most balanced research and prototype solution. Fully active systems may be justified for high-power tractors with severe load transients, whereas passive systems remain suitable only when cost and simplicity outweigh control performance. Technology selection should be supported by full-life-cycle converter loss, component aging, fault tolerance, and maintenance analysis.

Regenerative braking converts kinetic energy into electrical energy during deceleration, but tractor recovery potential is lower and more variable than in road vehicles because field speed is low, tire-soil adhesion is uncertain, and PTO or hydraulic loads may dominate the energy balance. Recovery control must therefore coordinate motor torque, friction braking, battery limits, wheel slip, and implement safety rather than maximize recovered energy alone. Fig. 5 summarizes the principal energy-management classes.

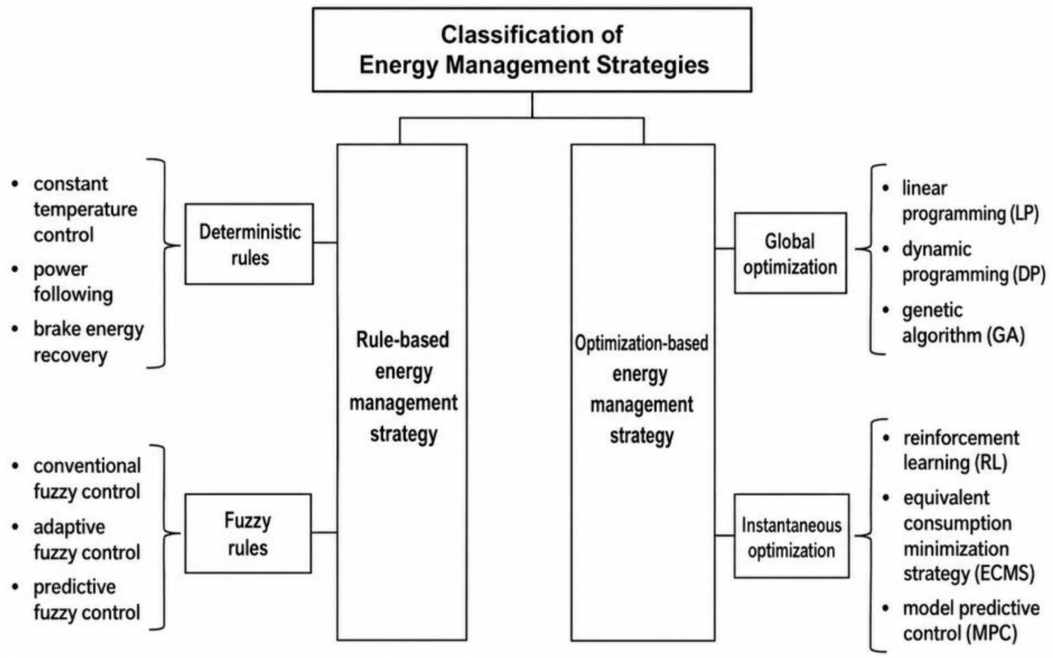

Fig. 5 - Classification of energy-management strategies

Rule-based strategies have low computational demand and predictable safety behavior, while model-predictive and learning-based methods can exploit load forecasts and repeated field patterns. International studies on off-road plug-in hybrids and parallel or series hybrid tractors report progress from offline global optimization toward operation recognition, predictive control, and real-time validation *(Ghobadpour et al., 2021; Mocera, 2021; Zhang et al., 2023; Yan et al., 2024; Zhao et al., 2024a)*. However, reported gains are not directly comparable because duty cycles, SOC boundaries, component maps, and baseline controllers differ.

Accordingly, advanced energy management should be evaluated against a transparent baseline using energy consumption, battery aging, hydrogen or fuel use, tracking error, computational time, and safety constraints. A numerical improvement obtained in one cycle is not sufficient evidence of technology readiness without real-time implementation and multi-condition field validation.

Current bottlenecks include weak adaptation to low-adhesion roads, saturation of battery charge acceptance during long descents, limited coordination among traction, hydraulic, hitch, and PTO subsystems, and the absence of standardized agricultural duty cycles. These gaps explain why many high-performing simulation strategies remain at laboratory or prototype maturity.

Agricultural operations require different combinations of vehicle speed, PTO speed, draft force, and hydraulic power. Adaptive strategies have improved cruising range, disturbance suppression, and PTO response *(Ding et al., 2024; Liao et al., 2024; Zhang et al., 2024; Zhou et al., 2024)*. Future controllers should identify the current operation and soil-load state online, but they must remain computationally lightweight and retain a validated fallback mode.

Power-output and PTO coordination

Electric tractors must divide available power among traction, PTO, hydraulic, and auxiliary loads. Mechanical coupling provides a direct and robust path for power splitting, whereas multi-motor architectures provide flexible electronic allocation. The latter can shift motor operating points and decouple traction from PTO speed, but increases inverter count, calibration effort, and fault-management requirements. A representative architecture is shown in Fig. 6.

Dual-motor coupling has expanded operating-mode coverage and improved plowing efficiency, but mechanical complexity and cost increase with the number of clutches and gear paths. Power-allocation strategies based on dynamic programming, Pontryagin's minimum principle, stochastic optimization, and load following have reduced equivalent fuel or energy consumption in specific tasks *(Li et al., 2019; Li T.H. et al., 2024; Zhang et al., 2023)*.

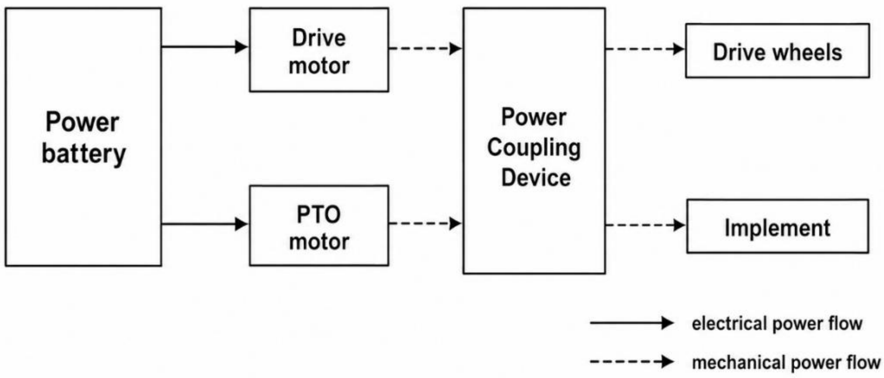

Fig. 6 - Power transmission system of the electric tractor

A key research priority is the integrated management of electrical, mechanical, hydraulic, and thermal systems, together with the development of standardized implement interfaces. Controller performance should be evaluated under simultaneous traction and PTO transients rather than only under steady-state loads. Evaluations should report torque reserve, PTO speed deviation, energy consumption, response time, and fault-recovery performance.

Load-following control is suitable for conventional operations involving variable draft; tractor–implement attitude coordination is required when working depth and posture determine agronomic quality; and multisource coupling is appropriate for high-power combined operations. These control modes are complementary rather than mutually exclusive. A field-ready system should switch between or blend them based on task recognition while maintaining slip, PTO speed, hitch position, and energy consumption within prescribed limits *(Xie et al., 2023; Yang F.Z. et al., 2023)*.

INTELLIGENT CONTROL AND DIGITAL DEVELOPMENT

Electric power steering replaces continuously driven hydraulic assistance with motor torque commanded from steering torque, angle, and vehicle-state signals. It improves controllability and enables automatic guidance, but agricultural deployment also requires high shock-load tolerance, sealing, redundancy, and safe manual fallback. Performance should be compared using steering effort, tracking error, response time, returnability, energy use, and fault behavior rather than road-feel metrics alone.

An electric hitch can regulate implement position and draft without continuous hydraulic throttling. Position, draft, and attitude feedback permit precise depth control, but motor and reduction mechanisms must withstand impact loads and contamination. Recent work has combined inclination sensing, force-position feedback, and fuzzy-PID coordination to improve body-implement attitude and tillage-depth stability *(Xie et al., 2024; Yang F.Z. et al., 2023; Zhang et al., 2022)*.

The main design trade-off is between the energy efficiency and controllability of electromechanical actuation and the overload capacity of hydraulics. Hybrid electro-hydraulic solutions may therefore remain preferable for high-power implements until compact actuators, impact protection, and thermal performance are validated.

Field evaluation should report depth error, draft-force fluctuation, settling time, energy consumption, mechanical temperature, and failure response across soil types and travel speeds. Without these common metrics, algorithm comparisons remain predominantly qualitative.

Autonomous navigation integrates GNSS/RTK, inertial sensing, perception, localization, path planning, and steering control. Early single-sensor guidance established the feasibility of automatic tractor steering, whereas later agricultural-robot studies emphasized modular platforms, sensor fusion, safety, task planning, and whole-farm economics *(Thuilot et al., 2002; Pedersen et al., 2006; Slaughter et al., 2008; Bechar and Vigneault, 2016; Grimstad and From, 2017; Shamshiri et al., 2018; Fountas et al., 2020; Lowenberg-DeBoer et al., 2020)*. For electric tractors, navigation accuracy must therefore be assessed together with energy use, implement performance, intervention frequency, and functional safety.

Linear, PID, optimal, model-predictive, and learning-based controllers provide different balances of computation, robustness, and curvature tracking. Recent tractor studies have used multi-body simulation, BeiDou/RTK, 5G monitoring, and resistance-adaptive control *(Jeon et al., 2023; Luo et al., 2025; Tian et al., 2024; Wang Q. et al., 2025)*. Commercial maturity is limited by obstacle perception, functional safety, remote supervision, and validation under dust, vibration, crop occlusion, and intermittent communication.

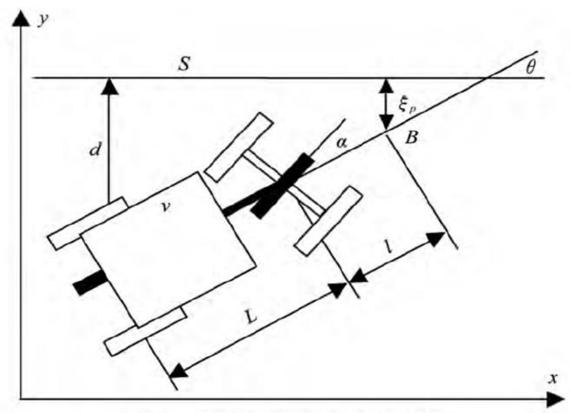

Fig. 7 - Tractor dynamic model

IoT integration can connect tractor, implement, operator, and service platform for condition monitoring and scheduling *(Wen and Wang, 2022; Zhao et al., 2023)*. However, interoperability, cybersecurity, data ownership, and degraded-mode operation must be treated as engineering requirements rather than later software additions.

System simulation and digital twins. General-purpose platforms such as MATLAB/Simulink, AMESim, ADAMS, AVL-Cruise, and multi-body tools support subsystem and vehicle development, but the literature still relies heavily on isolated models. Hardware-in-the-loop and model-based design have improved controller verification before field trials *(Mocera, 2021)*, while digital agricultural-robot platforms demonstrate the value of modular hardware and reusable software *(Grimstad and From, 2017)*. A tractor digital twin should link battery aging and thermal behavior with traction, PTO, hitch, hydraulics, navigation, and task-level energy demand, and should retain parameter provenance for reproducibility.

BOTTLENECKS AND DEVELOPMENT PRIORITIES

Technical, component, and infrastructure bottlenecks

First, continuous high-power operation remains constrained by pack mass, usable energy, thermal limits, and charging time. The relevant requirement is task energy per hectare or per workday, including PTO and hydraulic demand, rather than nominal vehicle range. Modular batteries, field charging, and exchange can reduce downtime, but require compatible interfaces and farm-level power planning *(Wallander et al., 2025)*.

Second, battery, motor, inverter, transmission, hydraulic, and PTO systems are still frequently optimized separately. Integrated optimization is needed to avoid response lag, oversizing, and energy transfer among subsystems. The absence of standardized agricultural duty cycles makes reported efficiency and endurance difficult to compare across studies.

Third, reliability evidence is weaker than performance evidence. Batteries, connectors, sensors, inverters, and distributed drives must tolerate dust, mud, water, chemicals, vibration, impact, and wide temperature ranges. Accelerated laboratory tests should be correlated with multi-season field data and accompanied by maintainability and fault-recovery analysis.

Components and standards. Tractor-specific component and interface standards remain incomplete. Communication, high-voltage safety, charging, battery exchange, electric implements, and diagnostic interfaces should be harmonized while permitting multiple power classes. Domestic localization should focus not only on nominal performance but also on consistency, sealing, thermal design, and service life.

Infrastructure and economics. Sparse rural charging, limited grid capacity, seasonal utilization, and insufficient service networks can offset powertrain advantages. Techno-economic and life-cycle studies show that outcomes are highly sensitive to annual use, electricity supply, battery replacement, charging strategy, and fleet logistics *(Mousazadeh et al., 2011; Lagnelöv et al., 2021; Vogt et al., 2021; Beligoj et al., 2022; Wallander et al., 2025; Ali et al., 2025)*. Broader automation studies likewise show that machine utilization, scale, labor substitution, and timeliness determine economic feasibility *(Pedersen et al., 2006; Lowenberg-DeBoer et al., 2020)*. Deployment assessments should therefore report scenario assumptions and sensitivity ranges rather than a single payback value.

Development priorities and research agenda

Technology and validation. Near-term research should prioritize validated tractor-specific batteries, high-efficiency low-speed motors, robust power electronics, and integrated traction-PTO-hitch control. Shared duty cycles and reporting metrics should be established for plowing, rotary tillage, seeding, transport, and mixed operations. These benchmarks should include energy per hectare, work rate, slip, PTO-speed error, component temperature, degradation, and failure response.

System integration and industrialization. Medium-term development should combine reusable multi-domain models, digital twins, condition-aware energy management, and modular charging or battery exchange. Long-term industrialization requires interoperable interfaces, functional-safety and cybersecurity requirements, recycling and second-life pathways, rural energy infrastructure, and total-cost and life-cycle assessment. A staged progression from simulation to hardware-in-the-loop, prototype, multi-condition field test, and multi-season demonstration would make maturity claims transparent and comparable.

CONCLUSIONS

Electric tractors have evolved from isolated prototypes into integrated battery-electric, hybrid, fuel-cell, and autonomous systems. The available evidence does not support a universally applicable powertrain architecture. Battery-electric systems are best suited to predictable low- and medium-power operations, hybrid systems remain practical for prolonged heavy-load operations, and fuel-cell systems offer rapid refueling but continue to be constrained by durability limitations and insufficient hydrogen infrastructure. Across all architectures, representative duty-cycle characterization and whole-system integration are more important than nominal component ratings.

A major limitation of the existing literature is its reliance on single-condition simulations and subsystem-level testing. Reported improvements are difficult to compare because studies differ in tractor power class, soil conditions, implements, reference systems, and evaluation metrics. International studies have demonstrated meaningful reductions in life-cycle environmental impacts and operating energy consumption. However, battery manufacturing, annual equipment utilization, charging logistics, and the electricity-generation mix can substantially influence these benefits. Performance claims should therefore be supported by uncertainty analyses and evidence concerning reliability, economic viability, and life-cycle impacts.

The highest research priorities include standardized agricultural duty cycles; pack-level safety and aging validation; integrated energy management for traction, PTO, and hitch systems; reusable multidomain models; modular field energy-replenishment systems; and interoperable standards for high-voltage systems and communication protocols. Technological progress should be demonstrated through a traceable validation sequence extending from simulation and hardware-in-the-loop testing to field trials conducted under multiple operating conditions and over multiple seasons. Such an evidence chain is essential for transforming promising algorithms and prototypes into reliable, economically viable, and scalable electric tractor systems.

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