



REVIEW ARTICLE

Mitigating subsoil compaction through autonomous modular machinery: A review of soil-machine interactions and sustainable agronomic practices

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Abstract

The preservation of soil structural integrity and optimal root development in smallholder agroecosystems is increasingly compromised by conventional, mass-dependent agricultural machinery. This review evaluates the agronomic implications of transitioning from heavy draft power to scale-neutral, autonomous modular swarms within fragmented farming systems (subplots under 2 hectares). Systematic analysis of 40 studies (via Scopus and Web of Science) demonstrates that conventional high-axle-load machinery induces deep subsoil stress cones. These pathways impede essential nutrient uptake, limit water infiltration and ultimately stunt plant physiological development. Conversely, purpose-built, lightweight autonomous platforms confine mechanical load impacts to the topsoil layer. This critical engineering shift preserves subsurface soil porosity, sustains a viable and highly active rhizosphere and prevents long-term structural degradation. Furthermore, the integration of sensor-driven precision navigation facilitates a 15–20 % reduction in basal fertiliser application. This optimises plant nutrient use efficiency while mitigating runoff into surrounding ecosystems. Adopting these systems yields operational efficiencies, including an 8–12 % reduction in overlap and a 6–10 % decrease in fuel consumption. These effects vary by soil texture, moisture and root architecture, being most pronounced in compaction-prone soils (e.g., Vertisols) susceptible to degradation. While socioeconomic barriers to adoption exist for marginal farmers, the primary agronomic benefit of autonomous swarms lies in their immediate capacity to halt anthropogenic soil compaction. Modular autonomous mechanisation offers a promising agroecological pathway, with potential to help maintain subsoil health, promote root proliferation and secure yields in vulnerable environments.

Keywords: agricultural robotics; agroecology; precision agronomy; smallholder mechanisation; soil porosity

Introduction

Smallholder farming systems-operationally characterised by resource-constrained family farming, diversified cropping and typically landholdings under 2 hectares in densely populated regions like South Asia and sub-Saharan Africa-comprise approximately 80 % of global farms and remain the backbone of agricultural production (1–4). Despite their disproportionate contribution to global food security, these systems are increasingly constrained by seasonal labour shortages, escalating input costs and asymmetrical access to appropriate mechanisation. Historically, agricultural engineering has pursued economies of scale by increasing the axial load and field capacity of conventional machinery. However, these empirical scaling laws fail in smallholder contexts due to structured

land fragmentation, reduced tractive efficiency in confined plots and thin rural credit markets, all of which impede the adoption of heavy machinery (2, 5, 6). Additionally, changing demographic situations-whether in terms of rural exodus and increasing wages in rapidly developing regions or persistent underemployment in others demand regionally distinct mechanisation pathways-deploying labour-substituting automation in high-wage zones versus scale-neutral shared services in labour-surplus areas-to overcome seasonal bottlenecks without triggering severe socio-economic disruptions (7–11). Consequently, the structural and demographic realities of smallholder farms demand scale-neutral technologies capable of operating within fragmented geometries without the prohibitive capital barriers of conventional machinery.

Such machines represent an intervention that will disrupt the system by providing increased efficiencies, safer work environments and even provide a remedy for the acute shortage of the labour force (12, 13). Unlike other forms of mechanisation, autonomous technology, from retrofit Global Positioning System (GPS) autosteering systems up to specialised robotic platforms, ensures the precision application of inputs, hence reducing the agrochemical waste. The technology greatly optimises the usage of basal agrochemicals due to its capability to deliver site-specific treatments while improving the execution of critical field operations at optimal times without reducing crop production (5, 14). From a soil mechanics viewpoint, transitioning to lighter, purpose-built autonomous platforms significantly reduces-though does not eliminate-subsoil compaction risk, provided that low contact pressures (typically < 50 kPa) and controlled traffic frequencies are maintained to protect soil porosity and root architecture. However, despite the benefits provided by such engineering and agronomic interventions, the cost remains a significant challenge. Although retrofitted autosteering equipment provides a starting point, the adoption of full autonomy often faces barriers in the form of expensive capital investments that weigh heavily on small-scale farmers (15, 16). In many developing nations, these smallholders operate strictly as marginal farmers with severely constrained purchasing power. Consequently, if these vulnerable populations are to capture the high operational and agronomic efficiencies of automation, these prohibitive capital costs dictate that adoption will require innovative financing approaches (17).

Despite the rich literature on performance standards of automation in big business-oriented companies, an essential lack of information exists about context-dependent conditions and socio-technical implications of this technology in extremely fragmented settings. To bridge this information void, a preferred reporting items for systematic reviews and meta-analyses (PRISMA)-guided systematic review protocol (synthesising literature from 2000 to early 2026 across major academic databases) evaluates data from 40 peer-reviewed empirical studies and technoeconomic models. This study analyses how regional labour markets, socio-economic restrictions at local levels and geometric restrictions influence the use of autonomous machines on the field that are less than 2 hectares. By synthesising these peer-reviewed datasets alongside insights from official agricultural extension web portals and institutional repositories, this review establishes the operational framework required to transition agricultural automation from experimental pilots into an economically viable, socially equitable and agronomic tool for smallholders.

Materials and Methods

This systematic review was carried out strictly according to PRISMA 2020 criteria. A comprehensive literature search was conducted across major databases such as Scopus, Web of Science, ScienceDirect, IEEE Xplore and SpringerLink for articles published between January 2000 and early 2026.

Table 1. Systematic review characteristics and study quality

Study focus	Number of included studies	Primary methodology	Geographic focus	Quality rating (High/Med/Low)
Autonomous field platforms	12	Empirical field trials	Global (High-income/Emerging)	High
Retrofit/Guidance systems	10	Technoeconomic modelling	Europe/North America	High
Smallholder adoption pathways	8	Socioeconomic surveys	South Asia/Sub-Saharan Africa	Med
Labour dynamics and displacement	10	Longitudinal regional studies	South Asia/Global South	Med

Search strategy and eligibility criteria

The search strategy was developed to identify the interaction between autonomous and semi-autonomous farm machinery and smallholder farm management systems, which for the purposes of this review were identified as farms of less than 2 hectares. Comprehensive database searches were conducted between 10 and 15 January 2026. The standardised search string applied across all platforms was: ("autonomous machinery" OR "agricultural robot*" OR "swarm robotics" OR "autosteer") AND ("smallholder" OR "small farm" OR "fragmented land") AND ("soil compaction" OR "agronomy" OR "technoeconomic" OR "labour"). The focus on socio-economic effects of scale-independent technology led to an emphasis on economically quantifiable variables such as capital outlays, cost of operations, return on investment (ROI), net present value (NPV), payback periods, cost of production and labour shifts. To maintain the highest scientific standards of validity and reliability, the inclusion criteria were restricted to peer reviewed empirical evidence and technoeconomic modelling. Studies were explicitly excluded if they were grey literature, focused exclusively on large-scale agribusiness applications without a scale-neutral comparison, or lacked quantifiable metrics.

Data extraction and quantitative synthesis

To address the structural diversity of the literature that was used for data collection, a common data extraction procedure was employed to maintain the integrity of the calculations that would be performed using the aggregated data. Data on efficiencies (such as reductions in fuel, fertiliser and pesticide consumption) and socio-economic shifts (operationally defined as transitions from manual farm labour to technical machine operation or regional migration) were included only if they were clearly defined and verified through a standardised risk-of-bias quality appraisal. Financial metrics like ROI and payback periods were analysed across distinct operational access arrangements, including individual smallholder ownership, cooperative machine-sharing pools and commercial custom-hiring services. The first search through the database generated 812 citations and these were then exported to Zotero reference management software for duplicate removal and initial screening. Through a thorough two-stage screening procedure, where title and abstract are screened first and then full texts assessed for eligibility, a total of 40 articles met the inclusion criteria and were therefore included in this review, as shown in the PRISMA flow diagram (Fig. 1). As a necessary methodological limitation, it must be noted that both the two-stage screening process and the final data extraction were conducted entirely by a single reviewer. The important features of these articles in terms of methodology used technologies and quality are summarised in Table 1.

Technological typology and power requirements

The small-scale deployment of autonomous agricultural equipment may be generally categorised into two different typologies: retrofitted conventional tractors and specific task-oriented purpose-built robots (12). Retrofitted technologies, which utilise GPS, telematics and

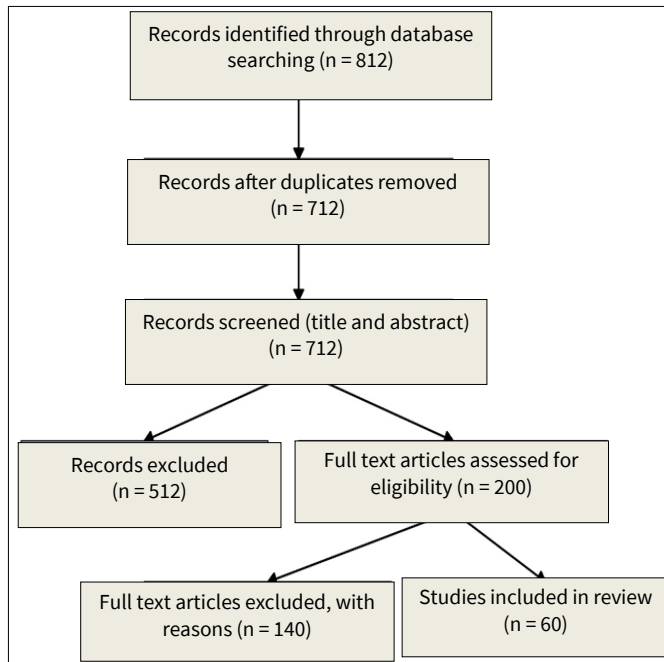


Fig. 1. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram for study selection.

autosteer technology integrated into the mechanical and hydraulic system of a base tractor, are merely improvements and do not involve any changes in the design of the vehicle, consequently, they inherit all of the vehicle's geometric constraints and axle-load capacity (16, 18). Conversely, purpose-built autonomous agricultural equipment provides greater flexibility, optimisation and versatility. These very specialised and lightweight devices, including robotic weeders, autonomous crop sprayers and precision rice transplanters, initiate a shift in the paradigm of the farm power dynamic (19, 20). The concurrent execution of diverse field tasks by lightweight autonomous vehicles greatly increases operational efficiency while eliminating all the agronomic concerns related to high axle loads (21). Specifically, purpose-built swarm robots typically operate with axle loads well under 500 kg, a stark contrast to conventional utility tractors that frequently exceed 4 to 6 tonnes, thereby fundamentally altering the soil pressure dynamics.

The implementation of such systems defies the traditional agricultural engineering design framework, which historically relies on classical drawbar mechanics where maximising tractive efficiency requires substantial machine weight to enhance soil-tire interaction and drawbar performance. However, the academic discourse proves that the same traction can be provided with the help of modular and lighter pieces of machinery (17, 19). This practice obviates the need for excessive diesel consumption to overcome the large rolling resistance of heavy equipment. In fragmented spatial landscapes of small farms, separation of the draft needs from the mass of machines is inevitable (17, 22). The scale-neutrality of autonomous platforms stems from the replacement of the principle of heavy draft force with more efficient drivetrains and lower speed of operations (12). This design solution provides better specific energy consumption since a larger amount of energy produced can be used for work on the field itself, without any need to compensate for rolling resistance. Empirical models indicate that conventional heavy tractors dissipate up to 20–30 % of their generated engine power merely overcoming soil deformation and rolling resistance, whereas lightweight autonomous platforms can reduce these draft-related energy losses by as much as 40–50 %. Moreover, as compared to traditional tractors, whose engines

always operate at high speeds despite the absence of immediate traction needs, special autonomous devices like automated rice transplanters utilise adaptive power management strategies and variable-speed electric motors that dynamically adjust to real-time mechanical loads (20), yielding a measurable 15–25 % reduction in overall fuel consumption during field operations compared to fixed-RPM conventional engines

Technical parameters and field capabilities

The implementation of robotic machines into extremely fragmented smallholder farms leads to numerous challenges regarding navigation and machine control. This equipment needs an ability to make kinetic decisions, navigate stochastic terrains and turn sharply at headlands while being bounded by geometrical boundaries that require chassis to be light yet resilient enough (23). Technological superiority of such machinery stems not only from downsizing but from real-time environmental awareness; real-time kinematic (RTK)-GPS ensures centimetre-level trajectory tracking to eliminate overlap, while integrated soil sensors dynamically map spatial variability in compaction and moisture to optimise variable-rate tillage and input placement (24). It was proven by multiple empirical studies that retrofitted and embedded automated machines help reduce operational inefficiencies significantly. However, it must be noted that the subsequent efficiency metrics represent model-derived optima and context-specific field trial results, rather than universally guaranteed outcomes. Tilling and seeding with RTK guidance systems decreases spatial overlap by 8–12 % compared to manual conventional tractor operation, saving 6–10 % of specific fuel consumption per hectare (6, 14). In addition, the implementation of autonomous sprayers and robot weeders allows for achieving impressive agronomic efficiencies. Condition-dependent inputs applied via autonomous machinery make it possible to achieve a 15–20 % reduction in basal fertiliser application without affecting the yield (5, 14), as well as 25–40 % reduction in pesticide amount needed due to targeted treatment (18, 25). Moreover, advanced weed management systems integrate computer vision algorithms to differentiate crop plants from weeds via morphological and spectral feature extraction, enabling targeted micro-spraying or mechanical actuation; however, field efficacy remains constrained by technical challenges such as high crop-weed morphological similarity, variable natural lighting conditions and algorithmic processing latency (26, 27). However, temporal advantages of autonomous mechanisation are even more important than the accuracy of the latter one and comprise, for instance, the timing problems of the crop rotation practices such as high-density rice-wheat farming cycle in South Asia. Maintaining strict time limitations via autonomous harvesters in cases when time windows become shorter because of climate variability and labour deficiency allows reducing the level of post-harvest grain losses by 9 % (5, 20). This combination of information points to the fundamental evolutionary change in the domain of smallholder mechanisation, namely to the change from macro-scale tractive capacity to micro-scale resource optimisation (12). The aggregated agronomic and performance benchmarks supporting these operational efficiencies are detailed in Table 2.

Machine-soil interface and agronomic impact

The adoption of autonomous machinery in smallholder farms introduces a fundamental shift in the machine-soil interaction, mitigating the severe subsoil compaction caused by traditional high-axle-load mechanisation. Modern agricultural vehicles have

Table 2. Quantitative justification of economic outcomes and operational efficiencies by technology typology

Technology typology	Operational context and validation method	Reported economic metrics	Quantified efficiency gains	Explicit labour impacts	Key sources
Autonomous tractors (Retrofit guidance)	Simulated models (< 100 ha) and extrapolated field trials for grain crops.	ROI: 8–15 % Payback: 5–7 years NPV: Positive after 5 years	Fuel reduction: 10–15 % (via decreased operational overlap).	Operator labour reduction: 40–50 % (due to extended autonomous operating hours).	(15, 16, 22)
Robotic weeders (Purpose-built)	Technoeconomic modelling (1–5 ha) and field trials in high-value vegetable crops.	ROI: 12–20 % Payback: 6–8 years	Agrochemical input savings: 20–30 % (site-specific application).	Manual weeding labour reduction: 50–60 %.	(17, 19)
Autonomous sprayers	Field trials (< 5 ha) focusing on precision horticulture and cash crops.	ROI: 10–18 % Payback: 5–6 years	Pesticide volume reduction: 25–40 % (micro-targeted application).	Spraying labour reduction: 30–40 % (alongside reduced operator exposure to toxins).	(12, 25)
Digital guidance and autosteering	Adoption surveys and farm-level empirical data (< 50 ha).	ROI: 5–12 % Payback: 4–5 years	Operational spatial overlap reduction: 8–12 %.	Operator time savings: 20–30 %.	(18, 28)

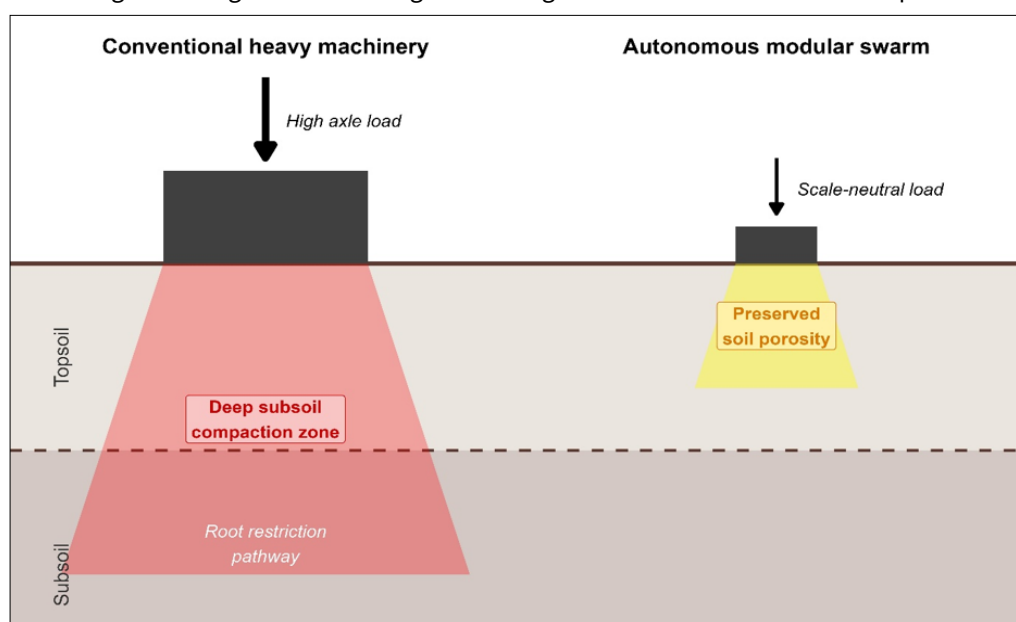
Quantitative metrics (ROI, Payback, NPV and efficiency gains) represent context-specific optima derived from localised models and should not be generalised across all agroecological zones. ROI: return on investment; NPV: net present value; ha: hectares.

grown so massive that their weights now rival those of prehistoric sauropods, inducing chronic subsoil stresses that exceed the safe mechanical limits for arable soil functioning (29). To accurately model this degradation, agricultural science frequently draws upon classical civil and geotechnical engineering principles, specifically applying Boussinesq's stress propagation equations. Originally developed to estimate how vertical stress spreads through soil beneath structural foundations, Boussinesq's theory demonstrates that while widened agricultural tires may maintain a constant surface contact stress, the total axle load ultimately dictates the depth and severity of subsoil stress propagation. Consequently, conventional heavy machinery causes deep, persistent stress cones that compress the soil matrix well below the tillage depth, fundamentally altering structural integrity and causing a deterioration of vital soil functions (30,31).

This geotechnical stress translates directly into severe agronomic limitations at the plant-soil interface. Empirical studies demonstrate that when soil penetration resistance exceeds the critical threshold of 0.8 to 2.0 MPa, root elongation rates are typically halved, restricting the proliferation of lateral roots and preventing access to deeper soil resources. This mechanical impedance is compounded by increased subsoil bulk density, which routinely exceeds critical limits (e.g., > 1.6 g cm⁻³ for loamy soils), triggering a subsequent reduction in total and air-filled porosity. When aeration porosity falls below the 10 % threshold required for optimal root respiration, localised hypoxia drastically restricts hydraulic conductivity and critical gas exchange. From a biological and

nutrient acquisition standpoint, this stunted root architecture severely shrinks the active rhizosphere, limiting the plant's ability to intercept essential, immobile nutrients such as phosphorus and potassium. Conversely, transitioning to scale-neutral autonomous modular platforms confines the mechanical load strictly to the topsoil. By separating draft requirements from vehicle mass, these lightweight swarms preserve subsoil porosity and maintain a highly active rhizosphere without necessitating heavy field consolidation. This fundamental difference in mechanical stress distribution and the resulting preservation of the subsoil matrix is conceptualised in Fig. 2 (13).

Beyond mitigating mechanical compaction, the agronomic superiority of autonomous systems relies heavily on the integration of precision sensor fusion and RTK-GPS navigation to optimise spatial efficiency (12). By treating fragmented sub-2-hectare plots as matrices of micro-variations, lightweight robotic platforms utilise tools like cosmic-ray sensors to map high-resolution spatial variability in soil moisture (32). Artificial intelligence algorithms process these localised environmental parameters, including evapotranspiration rates and phenological development stages derived from wireless sensor networks, to maximise input use efficiency (33, 34). This high-resolution data collection facilitates highly targeted treatments, enabling a 15–20 % reduction in basal fertiliser application while simultaneously minimising agrochemical runoff into surrounding ecosystems (5, 14). Ultimately, combining geotechnical load reduction with precision input management

**Fig. 2.** Conceptual schematic of soil compaction stress cones under conventional heavy machinery versus autonomous modular swarms.

positions autonomous mechanisation as a critical agroecological intervention for sustaining subsoil health and securing crop yields in vulnerable farming systems.

Economic viability and operational efficiency

Smallholder-based capital limitations represent a formidable obstacle to technological uptake, given that market valuations (estimated across developing regional contexts in 2024–25) indicate initial capital outlays starting around \$8000 for retrofitted digital guidance kits and exceeding \$120000 for full autonomous tractor platforms, with actual pricing varying substantially by manufacturer, level of autonomy and local market conditions (17). For marginal farmers, these extreme capital barriers are often completely insurmountable. Furthermore, beyond the initial purchase price, these autonomous systems present severe operational drawbacks. They require stable digital infrastructure, such as uninterrupted RTK-GPS or cellular connectivity, which is frequently absent in rural settings. Additionally, they impose high recurring maintenance costs and demand specialised diagnostic software for repairs-skills and tools that local village mechanics are currently unequipped to provide. Without adopting approaches such as shared economy principles and proper financing, implementation of such high-end technology may stay within the confines of pilot experiments (14, 35). Thus, the economic feasibility of autonomous machines is directly related to ownership and maximisation of the number of working hours annually. For dense agroecosystems such as the South Asian rice-wheat region, custom-hire and co-ownership models have been very successful in democratising access and bringing the time for payback period of investment to the economically feasible 3 to 5 years (5, 36). By contrast, in regions like Sub-Saharan Africa, with scarce mechanical infrastructure and limited access to rural credits, the payback periods can take more than eight years, discouraging individual adoption (11, 37). Nevertheless, despite these structural obstacles, tech-economic evaluations show extremely favourable economic outcomes if used in proper combination with value-added agriculture. Thus, robotic weeders show ROIs of 12–20 % in high-value cropping systems (17, 19), while autonomous sprayers provide ROIs from 10 % to 18 % owing to the significant reduction of costs on agrochemicals (12, 25). These highly favourable financial metrics are heavily context-dependent, relying on assumptions of optimal machine utilisation rates and crop value that may not reflect the stochastic realities of all smallholder environments. These indicators prove that despite structural barriers to private ownership for marginal farmers, service models have proven effective in overcoming the initial capital obstacle (38).

To make profits despite fast rates of capital depreciation, such autonomous systems must be either able to produce higher yields or to cut down on input costs considerably. As already noted above, the precision navigation is capable of optimising the inputs; an 8–12 % reduction of the spatial overlap in the process of tillage and seeding leads to 6–10 % lower fuel costs per hectare and consequently lower costs of standard operations (6, 14). Moreover, as opposed to conventional manually applied broadcasting, sensor-based autonomous application of fertilisers results in 15–20 % lower costs while still meeting the expected yields and thus protecting smallholders from unstable agrochemical markets (5). Apart from that, the value of time economy in fragmented fields is significant; autonomous systems avoid the delays between intensive crop

cycles and help to reduce the loss of harvest after rice production by 9 % (5). Although the historical literature emphasises the advantages of efficiency from operational use of machines in big businesses, small farms often suffer from lower absolute income because of inefficient use of machinery. Ultimately, the economic viability of autonomous agricultural machinery for smallholders is governed less by initial capital expenditures than by institutional mechanisms that maximise annual machinery utilisation.

Labour dynamics and access models

Introducing autonomous machines into smallholder farming systems leads to the creation of a complex dualism in terms of rural labour relations, which are primarily determined by regional demographics and the current state of the labour market. For instance, in South Asia, where there have been regular annual wage increases ranging from 6–8 % between 2005 and 2015 along with a massive exodus caused by the COVID-19 pandemic, introducing autonomous machinery has become a mandatory measure to help decrease seasonal dependence on labour. The replacement of labour through mechanisation is particularly important during timely transplanting and harvesting of crops, where any kind of delays cause serious threats to agricultural production and its overall profitability (36). On the other hand, in the regions with significant agricultural underemployment such as Sub-Saharan Africa, the introduction of labour-saving autonomous systems creates considerable socio-economic concerns about labour displacements (9, 11). Based on regional simulations, the large-scale use of autonomous machines may lead to a decline in the demand for casual farm labour by 12–18 % (9). Thus, in labour-abundant regions, the technology will create significant socio-technical barriers, which include unemployment, lack of skills and cultural resistance (9, 11). These stark regional disparities in adoption pathways and their corresponding labour impacts are spatially mapped in Fig. 3.

In order to overcome socioeconomic constraints in addition to high financial risks, the current literature largely emphasises the importance of strong institutional access models like cooperative ownership and government-sponsored custom hiring approaches (38). Latin American and South Asian experiences show how these types of access models have succeeded in providing advanced machinery to smallholders without the burden of upfront capital outlays (6, 36). Nevertheless, critical assessments of service provision in Brazil and Mexico indicate that the economic benefits obtained mostly benefit the service providers themselves rather than the smallholders individually (6). Contrarily, findings in India and Bangladesh show how cooperative ownership has been able to spread the economic benefit among the involved smallholders (5, 36). The sustainability of these sociotechnical transitions over the long term will be very dependent on localised institutional frameworks. In Sub-Saharan Africa, many donor-sponsored autonomous pilots showed successful short-term operation but swiftly faltered without external financial input because of the inherent lack of accessibility to rural credit markets (37). To avoid such institutional failure, specific enablers-including government incentives, digital farming extension programs and labour training programs are necessary. Such institutional frameworks not only quicken the process of adaptation but also ensure that the transition is socially inclusive, thus avoiding any worsening of the gap in wealth between the rich and poor farmers. Regional differences in adoption paths, impacts and sociotechnical barriers are shown in Table 3.

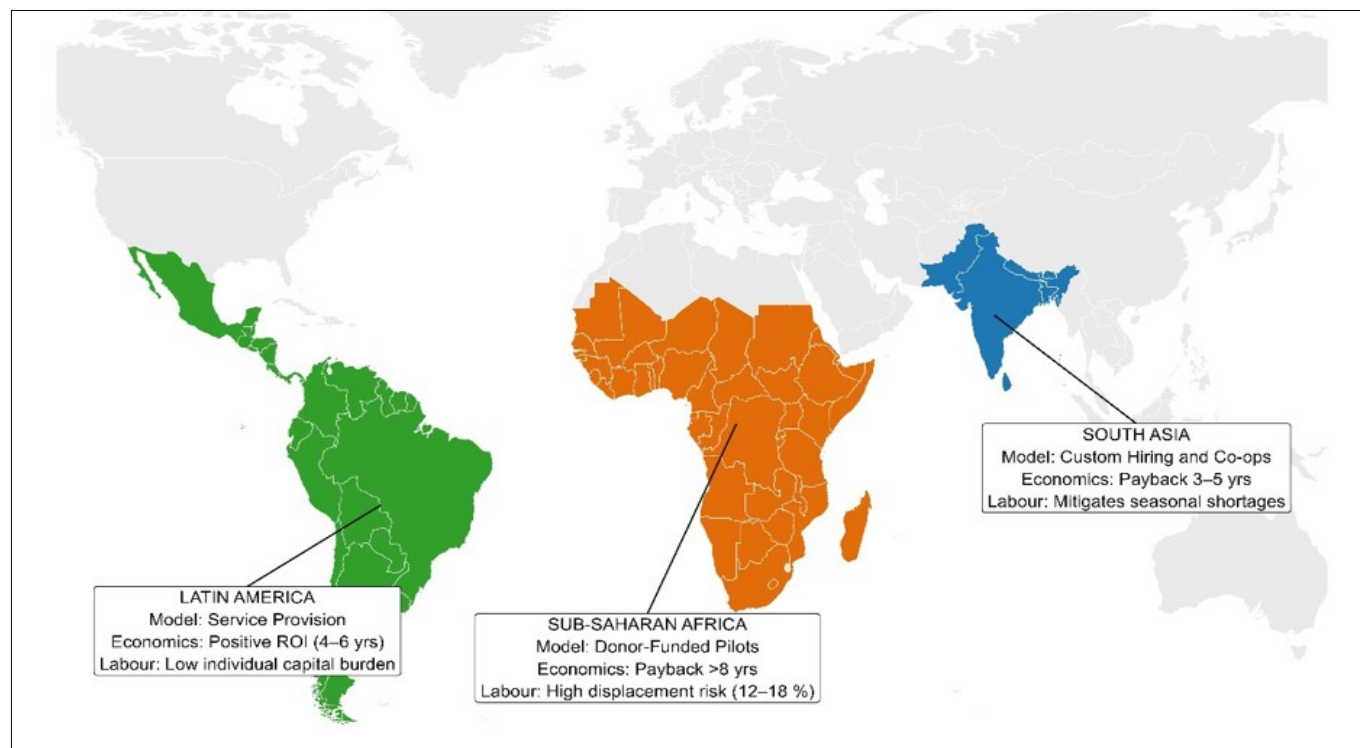


Fig. 3. Conceptual schematic mapping global mapping of regional adoption pathways, economic outcomes and labour dynamics for autonomous agricultural machinery in smallholder systems.

Table 3. Regional evidence synthesis: Adoption pathways, validated economic outcomes and socio-technical barriers

Geographic region	Dominant access model	Validated economic outcomes	Critical socio-technical barriers and labour impacts	Source evidence
South Asia (India, Bangladesh and Nepal)	Custom hiring centres and service provision models.	Payback compressed to 3–5 years due to high utilisation across fragmented plots.	Overcomes severe credit constraints; Acts as a critical intervention to mitigate acute seasonal labour shortages and wage inflation.	(6, 7)
Sub-Saharan Africa	Donor-funded pilot projects and heavily subsidised trials.	Independent profitability rarely demonstrated; payback periods frequently exceed 8 years.	Severe infrastructural gaps (rural credit, maintenance networks) Profound risk of casual labour displacement (estimated 12–18 % demand drop).	(2, 11)
Latin America	Cooperative ownership and specialised service models.	Positive ROI (4–6 years) with significantly reduced individual capital burdens.	Service providers often capture the majority of economic surplus; Requires highly robust local institutional frameworks to ensure equity.	(39)
Europe (Europe (e.g., Bavaria, alongside other key regional contexts discussed in the literature such as Thuringia, Switzerland and the Netherlands))	Sequential individual adoption (from basic guidance to full robotics).	Projected 15–20 % adoption growth trajectory among small-to-medium enterprises.	Highly reliant on baseline digital literacy and susceptible to gaps in state subsidy programs.	(28)

Validated economic outcomes remain highly context-dependent and are sensitive to local institutional frameworks and utilisation capacities.

Critical synthesis and evidence-gap analysis

Although the collected literature provides compelling evidence for the theoretical and practical merits of autonomous agriculture equipment, an in-depth analysis of all data shows considerable methodological flaws and disparities across different regions.

Methodological flaws and over-reliance on simulations

The first significant problem with existing research is excessive use of technoeconomic simulations based on optimistic assumptions. To accurately assess this viability, findings must be strictly distinguished: while empirical field trials consistently demonstrate high-confidence agronomic efficiencies at the machine-soil interface, the overarching economic metrics are predominantly derived from technoeconomic modelling. Several frequently cited economic models that base their assumptions about positive ROI and NPV figures on optimal performance of agricultural machinery without interruptions (16, 17). Consequently, while modelling

studies suggest highly favourable economic outcomes, these figures must be treated with qualifying caution as theoretical optima rather than guaranteed baselines, emphasising that robust sensitivity analyses incorporating operational downtime and variable field efficiencies are essential to improve model reliability. Nevertheless, real-life data gathered in smallholder environments demonstrate that these conditions are rarely met due to fragmented plots and lack of proper rural roads infrastructure, as well as periodic breakdowns of machines. Therefore, any simulation built on fields' geometry in Europe or North America greatly exaggerates economic benefits of these technologies in Asia or Africa.

Regional disparities and experimental bias

In addition, the consistency of the evidence is also heavily biased due to the way the experimental deployments were conducted. Within Sub-Saharan Africa, the cases of success involving autonomous technology largely come from highly subsidised pilot schemes

funded by donors (11, 38). These studies frequently overlook the actual market cost of capital, credit constraints and the lack of local support for maintenance and repair services, hence giving an over-idealised view of the technological potential. Therefore, while evidence from South Asia offers high confidence due to longitudinal surveys of established cooperatives, the data from Sub-Saharan Africa currently provides only low-confidence projections regarding long-term, unsupported sustainability. There is currently a significant shortage of robust longitudinal field tests evaluating the reliability of autonomous sensors and actuators in harsh, stochastic environments of small farms, such as monsoon rains and heat stress.

Crucial knowledge and evidence gaps

Indeed, the current systematic review highlights several crucial knowledge gaps that should be filled for autonomous smallholder mechanisation to move from an interesting theoretical concept to a concrete reality. First, there is a dire shortage of life cycle assessment (LCA) studies that would analyse the full environmental impacts of using swarm robotics versus the conventional methods of draft power. The latter is especially true regarding such factors as the degradation of batteries and the problems related to managing the electronic waste in the rural, developing parts of the world. Furthermore, the implications for climate resilience require formal investigation; while reduced compaction aids water infiltration, the operational reliability of delicate sensors under extreme weather events such as severe heat stress or monsoon conditions remains critically under-researched. Finally, current socio-technical evaluations fail to integrate gender dimensions, leaving it unclear

whether automation will disproportionately displace female agricultural labourers or successfully alleviate their historical physical drudgery. Second, even though the direct effects of replacing human labourers are well understood (9), there is a clear need for empirical studies on how the employment generation effects promised by agricultural digitalisation come about.

Engineering-economic adoption framework

To address the gaps existing between the engineering capabilities and reality of adoption discussed in this review, the following framework for Engineering-Economic Adoption is introduced (Fig. 4). This matrix describes the essential paths of decision making which enable smallholder farmers to move their systems from traditional mechanisation based on scale to an autonomous system. Grounded in sociotechnical transition theory, this framework illustrates that technological artifacts and institutional structures are co-evolutionary: A functional sociotechnical system cannot emerge through engineering design (scale-free modular units) or institutional policy in isolation, requiring synchronised co-development.

Research priorities

To bridge these identified gaps, future research must prioritise:

1. Executing localised LCAs focused on circular e-waste frameworks for autonomous batteries;
2. Conducting multi-season empirical trials testing sensor resilience in climate-stressed environments; and
3. Implementing gender-disaggregated longitudinal surveys to map the true socio-demographic impacts of automation.

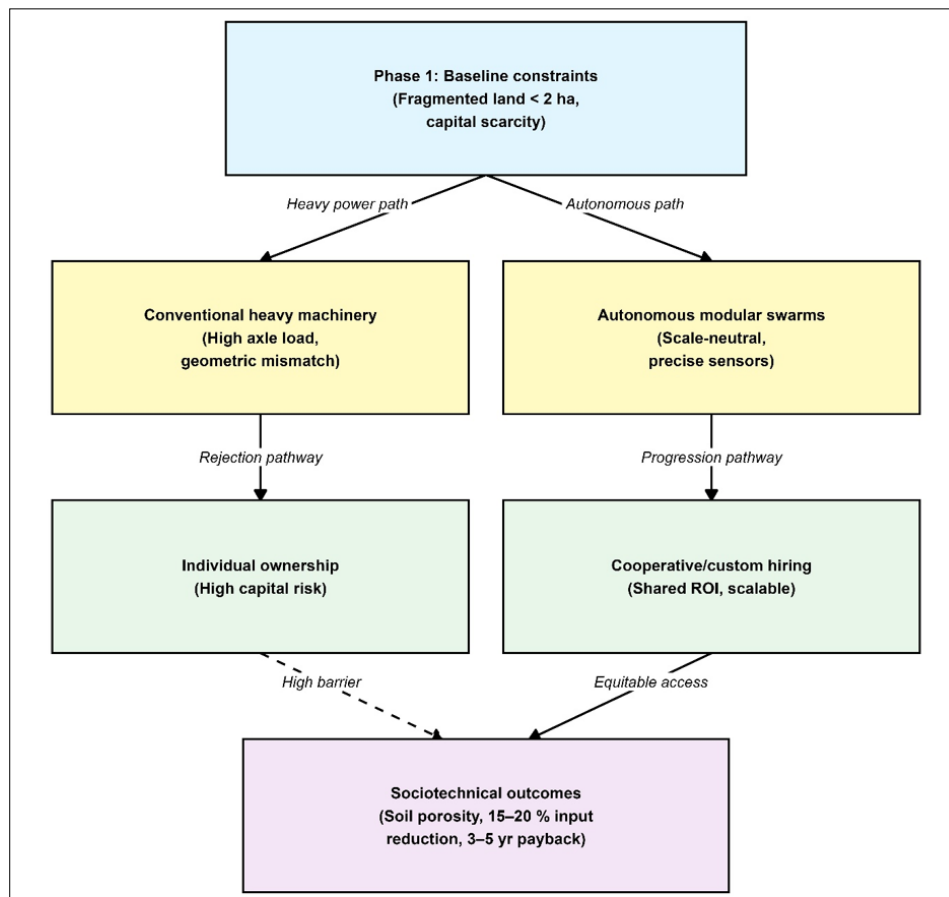


Fig. 4. Conceptual schematic flowchart of adoption pathways for conventional and autonomous agricultural machinery. This framework illustrates the divergent decision-making processes between traditional scale-based systems and scale-neutral automation. It highlights how integrating engineering innovations (e.g., lightweight, modular designs) with institutional interventions (e.g., custom-hire models) is essential to overcome the severe capital barriers faced by farmers on sub-2 hectare plots.

Conclusion and policy implications

In conclusion, the deployment of autonomous agricultural machinery drives a significant sociotechnical paradigm shift from scale-bound to scale-free mechanisation-achieving unprecedented operational flexibility and physical accessibility independent of landholding size. This modular autonomous mechanisation serves as a vital agro-ecological intervention essential for safeguarding key ecosystem services in smallholder systems, including soil structural preservation, enhanced hydrological regulation and minimised chemical leaching. From an engineering perspective, this paradigm shift bypasses the geometric constraints of sub-two-hectare plots and eliminates the problem of soil compaction. Furthermore, the integration of precision sensors significantly optimises input use efficiency, directly translating localised agronomic data into reduced operational overlap and minimised agrochemical dependency. However, synthesis of the literature indicates that widespread diffusion depends far less on raw technical capability than on local socioeconomic context and regional economic conditions. The dual sociotechnical impact of automation-acting as a labour-substituting measure in high-wage regions while presenting structural disruption in labour-surplus economies-demands highly context-specific strategies that account for labour augmentation, task displacement and emerging technical skill requirements. In the case of marginal agriculture, where there are very serious resource constraints, individually owned autonomous systems will not work. The process of modernisation of smallholding agriculture is entirely dependent on access through institutions and it was proven empirically that access is possible with the help of rental facilities and cooperatives. Crucially, these service models must be strictly regulated and governed equitably to ensure they do not inadvertently perpetuate structural inequalities, scenarios in which service providers capture most of the economic surplus while marginal farmers remain dependent.

Consequently, policy paradigms must shift away from isolated hardware subsidies toward a more holistic approach. In future, such interventions should ensure the development of effective cooperation networks, proper digital extension services and retraining programs that would help incorporate those labourers who have been displaced by agricultural mechanisation. Specifically, actionable policy instruments-such as state-backed cooperative grants and low-interest micro-credit guarantees-must be implemented within defined 3 to 5 year timeframes to absorb initial capital shocks. The underlying theory of change posits that linking these targeted financial subsidies directly to digital extension and retraining programs will empower local cooperatives to generate sustainable returns, thereby driving equitable and inclusive adoption. Furthermore, robust monitoring and evaluation frameworks must be embedded within these policies to continuously assess socioeconomic impacts and machine reliability. Given the inherent uncertainties of deploying novel technologies in stochastic environments, integrating automation into this supportive institutional framework offers a promising pathway for small-scale systems, provided that future longitudinal research rigorously validates these socio-technical and agronomic outcomes.

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Authors' contributions

NSP conceived the review study, participated in its design and coordination and drafted the manuscript. NK and SD conducted the comprehensive literature search and synthesised data on autonomous modular machinery. SBB and AS analysed subsoil compaction mechanisms and root restriction dynamics. N and SSD provided critical insights into agronomic parameters and revised the manuscript for important intellectual content. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

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