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Innovative ways of agricultural development in the Republic of Kazakhstan

Maxat Abraliyev [1]*, Galiya Akimbekova [2], Zhazira Kusmoldayeva[1], Onalbek Abraliyev[1], Moldir Kauymbayeva[3]

[1]Department of Management, al-Farabi Kazakh National University, 71 al-Farabi Ave., Almaty, 050040, Kazakhstan
[2] Kazakh Research Institute of Economics of Agro-Industrial Complex and Rural Development, 30B Satpayev St., Almaty, 050057, Kazakhstan
[3] Department of Veterinary Sanitary Examination and Hygiene, Faculty of Veterinary Science, Kazakh National Agrarian Research University, 8 Abay Avenue, Almaty, 050010, Kazakhstan

***.Corresponding author's E-mail:** *abraliyev_maxat@live.kaznu.kz*

ABSTRACT

This study determines which classes of agricultural innovation are economically justified under the factor prices, farm structure, and financing conditions prevailing in Kazakhstan and identifies the conditions under which their adoption becomes rational for the individual producer. This study applies partial-budget analysis in the ex-ante scenario tradition established in the economics of agricultural robotics. Cost, price, and policy parameters are drawn from the Kazakhstani market and official sources for 2023–2026; technical performance coefficients for AI-based targeted spraying are transferred from published field trials and treated as scenario bounds. The decision variable is the maximum investment a producer can justify over an eight-year horizon, evaluated at concessional and commercial discount rates across farm sizes from 1,000 to 20,000 hectares. Spring wheat production in Northern Kazakhstan operates at approximately zero economic profit in an average season, clearing at 4,400 KZT ha^{-1} at a yield of 12 c ha^{-1} and a price of 87,000 KZT ton^{-1}. AI-based targeted spraying reduces herbicide expenditure by 8,780 to 15,200 KZT ha^{-1}, a saving equivalent to a yield increase of 1.0 to 1.75 c ha^{-1} and amounting to two to three times the average gross margin. The binding constraint on adoption is the cost of capital rather than technical performance: concessional finance raises justifiable investment by 52%, an effect exceeding the entire range of technical performance uncertainty. The break-even sown area lies between approximately 1400 and 4,200 hectares depending on system price and financing terms. This study replaces the technological recommendations that dominate the regional literature with an economic decision rule specifying technology class, farm size, financing terms, and investment sequence. It further establishes that robotization and fleet renewal are complements in sequence rather than competing alternatives, and that service provision rather than purchase subsidy is the viable diffusion pathway for producers below the scale threshold.

Keywords: Agricultural innovation, Kazakhstan, Digitalization, Digital technologies, Technology adoption, Partial budgeting, Investment appraisal, Targeted spraying.

1. INTRODUCTION

Kazakhstan occupies an unusual position in the global agricultural economy. The country commands more than 200 million hectares of agricultural land, ranks among the world's leading wheat exporters, and serves as the principal grain supplier to Central Asia, yet its agricultural sector converts this endowment into output at a rate far below that of comparably endowed dryland producers. Wheat yields in Kazakhstan stood at roughly 1.33

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tonnes per hectare in 2016, against 2.95 tonnes per hectare in Russia (Tleubayev *et al.* 2022). The gap is not primarily a gap in natural conditions; it is a gap in the productivity with which land, labor, and capital are combined. This distinction matters for policy, because the two diagnoses imply entirely different remedies: the former would justify resignation, and the latter identifies an economic problem that innovation policy can address.

Farm-level evidence locates the problem inside the production unit rather than in the resource base. Stochastic frontier estimates for a sample of wheat-producing farms in Kazakhstan and Russia indicate that nearly one farm in five operates at a technical efficiency level below 60%, implying substantial unrealized output attainable with the inputs already employed (Tleubayev *et al.* 2022). Where such inefficiency persists, the marginal return to additional land or additional subsidies is low relative to the return from measures that move farms towards the production frontier – technology, management capability, and institutions that transmit both. Growth in Kazakhstani agriculture has been predominantly extensive, driven by the expansion of sown area and budgetary transfers, whereas sustained income growth in the sector requires the intensive margin: total factor productivity (World Bank 2019; Tleubayev & Syzdykov 2025).

State support has been the dominant instrument of agricultural policy, but the empirical record on its effectiveness is uncomfortable. An analysis of farms in Kazakhstan and Russia finds subsidies to be negatively associated with technical efficiency, an outcome consistent with an income effect that weakens managerial incentives once part of farm income is guaranteed independently of performance (Tleubayev *et al.* 2022). Cross-country evidence points in the same direction: farm subsidies have, on aggregate, exerted a dampening influence on global agricultural productivity growth (Mamun 2024). National assessments identify design faults that plausibly generate this result: the absence of counter-obligations on recipients, weak monitoring, and an allocation skewed towards large agricultural enterprises that account for a minority of producers (Kazhiyeva & Zhailaubayeva 2022; OECD 2025). Studies on subsidy mechanisms for agricultural cooperatives in Kazakhstan report comparable problems of accessibility and administrative complexity (Alipbeki 2024; Siximbayeva *et al.* 2025). The policy question is therefore not whether support should exist, but whether its composition can be shifted from output- and input-linked transfers towards general services – research, extension, infrastructure, that raise the frontier itself.

Three structural constraints condition any innovation strategy: The first is capital. The renewal rate of the machine and tractor fleet has remained materially below the technologically optimal range, leaving a fleet whose average age increases operating costs and forecloses the adoption of technologies embodied in new equipment (OECD 2025). Second, the institutional framework governing land and credit must be improved. Kazakhstan's 2003–2005 land reform, though liberal in intent, did not activate a land sales market, reorganize the rental market in a top-down fashion with the state remaining the principal landlord, and did little to make owned land usable as collateral (Kvartiuk & Petrick 2021). Where land cannot serve as security, the credit constraint binds precisely on medium-sized producers most likely to adopt scale-neutral technologies. The third is human capital and digital infrastructure development. Empirical work on Kazakhstan finds that investment is the dominant determinant of agricultural output, while the measured effects of digital literacy and rural internet activity remain weak or negative, which is best read not as evidence against digitalization but as evidence that complementary skills and connectivity have not yet reached the threshold at which digital capital becomes productive (Bekbossinova & Doszhan 2025; Şengül *et al.* 2025).

These constraints explain why the economics of agricultural innovation cannot be reduced to a catalogue of available technologies. The classical adoption literature established that the diffusion of an innovation depends jointly on farm size, risk aversion, credit access, tenure security, human capital, and the information environment, and that these determinants interact (Feder *et al.* 1985). Contemporary work on precision technologies confirms this framework and adds the role of peer networks in shaping farmers' valuations (Blasch *et al.* 2022). For robotics specifically, systematic reviews of the economic literature find that profitability is scenario-dependent rather than general: automation pays where it displaces a costly and scarce input, and the reported break-even investments — a farmer able to justify up to €40,000 for a robotic weeder relative to manual weeding in labor-intensive organic production — are derived from cost structures very unlike those of extensive Kazakhstani grain farming (Lowenberg-DeBoer *et al.* 2020). Whole-farm analyses of autonomous equipment likewise show that the economic case rests on economies of size and the relative price of labor, capital, and fuel. Therefore, recommending robotization for Kazakhstan without an explicit cost structure is an assertion, not a finding.

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Climate change converts this from a question of comparative advantage into a question of sectoral viability. Projections indicate declines in Kazakhstani wheat yields of the order of 20% to 50% by 2050 under higher temperatures and reduced growing-season soil moisture, with adaptation measures – crop diversification, a shift away from water-intensive crops, water-saving irrigation, and improved soil management – carrying material fiscal and investment implications (Petrick & Götz 2019; World Bank 2024). Under such projections, productivity growth ceases to be an option for raising incomes and becomes the condition for maintaining current output levels.

1.1 Technology classes and a criterion of relevance

Inventories of agricultural technologies are readily available, but enumeration provides little guidance for policy: the economic value of a technology is not a property of the technology itself but of its interaction with the factor prices, farm structure and institutions of the system into which it is introduced. The adoption literature established this four decades ago – diffusion depends jointly on farm size, risk aversion, credit access, tenure security and human capital, and these determinants interact rather than operate independently (Feder *et al.* 1985). Contemporary evidence on precision technologies confirms the framework and adds the influence of peer networks on farmers' valuations of technology attributes (Blasch *et al.* 2022).

Kazakhstani grain production has three characteristics that together determine which technology classes can be economically relevant. It is extensive rather than intensive, so land is abundant and yields per hectare are low. It is capital-constrained, with a self-propelled machinery fleet at high average depreciation and a renewal rate that has only recently approached the technologically required range (Kurmanova 2022). In addition, it is credit-constrained in a structural rather than transitory sense, since the land reform of 2003–2005 did not establish land as usable collateral, leaving the state as the principal landlord and the rental market as the main channel of land access (Kvartiuk & Petrick 2021). A technology is therefore relevant to this system if it reduces variable input expenditure per hectare, requires modest incremental capital relative to the existing machinery stock, and does not presuppose credit access that Kazakhstani producers do not have.

Applying this criterion, four technology classes are examined below. Three further classes frequently discussed in the literature are excluded, with reasons given in Section 1.7.

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Four technology classes are examined below based on this criterion. Three further classes frequently discussed in the literature are excluded, with reasons given in Section 1.7.

1.2 Variable-rate and targeted application

Precision application covers a spectrum from variable-rate distribution across management zones to plant-level targeted spraying based on machine vision. The economic mechanism is input substitution: the technology reduces the physical quantity of herbicide, fertilizer, or seed required to achieve a given agronomic result, and the return accrues as a saving on a variable cost item rather than as an increase in output.

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This mechanism is the best match for Kazakhstani conditions. In extensive grain production, the two large variable items amenable to targeting are herbicides and fuel, and herbicide application is the operation for which quantified field evidence is available. Contemporary machine-vision systems activate individual nozzles only where weeds are detected, and published field-scale trials report savings that vary widely with weed pressure — a variability that is itself economically informative (Beckie *et al.* 2019), since it implies that the return is site-specific and cannot be assumed uniform across the northern grain belt.

Two qualifications follow from the economics literature. First, systematic reviews of agricultural automation find that profitability is scenario-dependent rather than general: automation pays where it displaces a costly or scarce input, and the published break-even figures derive from cost structures unlike those of extensive dryland grain farming (Lowenberg-DeBoer *et al.* 2020). Second, whole-farm analyses show that the case for autonomous and precision equipment rests on economies of size and the relative prices of labor, capital, and fuel (Lowenberg-DeBoer *et al.* 2021). Both qualifications point to the same conclusion: the relevance of targeted application to Kazakhstan is an empirical question about local factor prices, not a property that transfers with the machine. Section 3 addresses this question directly.

1.3 Satellite remote sensing

Satellite imagery supports vegetation index monitoring, yield estimation, and stress detection over large areas. Its advantage in the Kazakhstani context is that the marginal cost of covering an additional hectare is close to zero, making it the only class in this review whose economics improve rather than deteriorate with extensive scale. The public-good rationale is also strongest here: individual producers under-invest in monitoring because the information generated has positive externalities for neighboring farms, insurance pricing, and policy design.

Its limitation is that satellite data support diagnosis but not intervention. Vegetation indices identify where a problem exists; they do not apply the input that addresses it. Remote sensing therefore returns only when coupled with a delivery capability, which returns the analysis to the machinery constraint. Empirical work on Kazakhstan is consistent with this reading: investment emerges as the dominant determinant of agricultural output, while measured effects of digital literacy and rural connectivity remain weak, indicating that complementary capabilities have not yet reached the threshold at which digital capital becomes productive (Dauliyeva 2022; Bekbossinova & Doszhan 2025). Remote sensing is additionally relevant to the adaptation agenda, since projected declines in wheat yields under higher temperatures and reduced growing-season soil moisture make within-season monitoring more valuable (World Bank 2024).

1.4 Unmanned aerial vehicles

UAVs occupy an intermediate position between satellites and ground equipment, offering higher spatial resolution and flexible timing, with some platforms performing applications as well as observation. However, the economic case for extensive grain production is weaker than the technical one: the coverage capacity of a few square kilometers per day is poorly matched to holdings of several thousand hectares of uniform spring wheat, and per-hectare operating costs remain high relative to satellite alternatives with adequate resolution for the decisions actually taken in extensive systems. UAVs are therefore best understood as a diagnostic complement for targeted tasks, such as outbreak verification, damage assessment, and trial monitoring, rather than as a routine management tool for the northern grain belt.

1.5 Machine guidance and autonomous field equipment

GNSS guidance, section control, and auto-steer are established technologies with documented returns arising from reduced overlap in seeding, spraying, and fertilizing, and from extended working hours. Full autonomy is a later stage of the same trajectory. The economic analysis of autonomous arable equipment finds that the case rests on economies of size and the ability to substitute several smaller machines for one large one, with profitability sensitive to fuel and labor prices and the supervision time the equipment still requires (Lagnelöv *et al.* 2021; Lowenberg-DeBoer *et al.* 2021).

Two features of this class deserve emphasis for Kazakhstan. First, guidance and section control are prerequisites rather than alternatives for targeted application: a machine-vision spraying system requires a carrier platform with functioning boom height and section control. This creates a sequencing relationship between mechanization and automation, which is developed quantitatively in Section 3.6. Second, the labor-displacement rationale that dominates the international literature on field robotics carries limited weight here, because labor is not a large, separable cost item in extensive grain production. The return in Kazakhstan comes from input saving and operational precision, not from replacing operators.

1.6 Digitalization as an enabling layer

The four technology classes above share a common dependency that is easily mistaken for technology itself. Precision application requires positioning data and prescription maps; satellite monitoring requires the capacity to receive, interpret, and act on imagery; and autonomous equipment requires connectivity for supervision and telemetry. Digitalization is therefore best understood not as a fifth class of machinery (Ehlers *et al.* 2021) but as the layer of data, connectivity, and skills on which the other classes depend for their returns. This distinction matters because policy instruments that fund hardware without the enabling layer will not deliver the returns computed for the hardware.

Empirical work on Kazakhstan supports this reading in an initially counter-intuitive way. Estimates of the determinants of agricultural output find investment to be dominant, while the measured effects of digital literacy and rural internet activity remain weak or negative (Bekbossinova & Doszhan 2025). Read naively, this would suggest that digitalization does not raise productivity. Read as a threshold relationship, it suggests instead that complementary capabilities have not yet reached the level at which digital capital becomes productive: connectivity without an operational carrier platform, or prescription maps without variable-rate hardware, generate information that cannot be acted upon. The same interpretation is consistent with evidence that productivity in Kazakhstani agriculture responds primarily to integration with external markets and capital rather than to domestic technological availability alone (Şengül *et al.* 2025).

Three components of the enabling layer are relevant to the assessment that follows. The first is data as a public good: monitoring information generated on one holding has positive externalities for neighboring farms, insurance pricing and policy design, which implies systematic under-investment by individual producers and a rationale for the public provision of the satellite and agrometeorological layer. The second is human capital: the classical adoption literature identifies education and information access as determinants of diffusion alongside farm size and credit (Feder *et al.* 1985), and contemporary evidence shows that farmers' valuations of precision technologies are shaped by peer networks and demonstrated experience rather than technical specifications (Blasch *et al*. 2022). The third is machine-readable land and tenure records, the absence of which prescription mapping and field-level accounting remain fragmented – a constraint tied directly to the incomplete institutionalization of land rights (Kvartiuk & Petrick 2021).

The implication of the present analysis is that the returns computed in Section 3 are conditional on the enabling layer rather than independent of it. Where connectivity, skills, and interoperable data are absent, the same machine will deliver lower realized savings than the scenario bounds indicate. Digitalization accordingly enters this study not as a separate object of appraisal but as a precondition whose absence would shift the realized outcome towards the lower end of the scenario range, and as an argument for allocating part of state support to general services rather than to output-linked transfers (Ehlers *et al.* 2021; OECD 2025).

1.7 Technologies excluded from the analysis

Three classes frequently discussed in reviews of agricultural innovation are excluded on economic grounds. Vertical farming addresses a scarcity of horizontal space that Kazakhstan does not face, and its energy intensity and narrow crop range make it irrelevant to cereals. Super-absorbent soil polymers are applied at per-hectare rates that are prohibitive at the scale of extensive grain farming. Horticultural harvesting robotics targets labor costs in crops Kazakhstan produces at a limited scale. These exclusions apply the criterion of Section 2.1 rather than judging the technologies themselves.

1.8 Research gap, aim and objectives

The review yields a clear ordering. Targeted application has the strongest economic case because it acts on a large variable cost item; satellite monitoring has the most favorable cost structure at an extensive scale but requires a delivery capability to generate returns; UAVs are a diagnostic complement rather than a routine tool; and machine guidance is a precondition for the first class rather than a substitute for it.

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The literature does not provide the magnitude of these returns under Kazakhstani factor prices. The published performance coefficients derive from other production systems, and the relevant cost structure – the price of herbicide per hectare, the cost of capital actually faced by producers, and the distribution of farm sizes – is national rather than transferable. Assessing whether any of these technologies is economically justified therefore requires an explicit calculation of Kazakhstani data, which the following section provides.

Despite the extensive descriptive literature on the agro-industrial complex, the economic question central to policy design remains open: which innovations are economically justified under Kazakhstani factor prices, farm structures, and institutional constraints, and what sequence of policy measures would make their adoption rational for the individual producer? Existing studies either evaluate state support without reference to technology or describe technologies without reference to the conditions under which their adoption is profitable (Dauliyeva 2022; Bekbossinova & Doszhan 2025; Siximbayeva *et al.* 2025). This study addresses this gap. Its objectives are (i) to assess the productivity performance of Kazakhstani agriculture and identify the sources of the observed efficiency gap; (ii) to evaluate the composition and effectiveness of current state support against the criteria established in the productivity literature; (iii) to determine, through partial-budget analysis under Kazakhstani cost conditions, which classes of innovation are economically justified at prevailing factor prices; and (iv) to derive a sequenced set of policy measures consistent with those findings. The contribution is to move the discussion of agricultural innovation in Kazakhstan from technological description to economic assessment, and to specify the institutional preconditions – collateralisable land rights, functioning credit markets, extension capacity and digital skills –without which the technologies themselves will not diffuse (Rizov 2005; Kvartiuk & Petrick 2021; Kurmanova 2022).

The practical significance of the study lies in three deliverables for policy and producers. First, it provides an investment decision rule expressed in the units in which producers plan – the maximum outlay justified per farm size and the minimum sown area at which a given system price is recovered, so that the appraisal can be repeated by any enterprise once a supplier price is known. Second, it identifies the policy instrument with the highest leverage per budget tenge, showing that broadening concessional leasing outperforms raising purchase subsidies and that the present differentiation of subsidy rates by country of manufacture works against the technology class with the largest measured input saving. Third, it establishes an expenditure sequence – fleet renewal before automation — and identifies service provision as the diffusion channel for producers below the scale threshold, which together define who can be reached by which instrument.

2. MATERIALS AND METHODS

2.1 Research design

This study applies partial-budget analysis in the ex-ante tradition established in the economics of agricultural robotics (Lowenberg-DeBoer *et al.* 2020). The analysis is a scenario simulation calibrated on published parameters, not an econometric estimation of primary farm-survey data, and this status is stated explicitly because the two designs support different kinds of inference. The purpose is to establish whether a technology class can be economically justified under a defined set of prices and financing terms, not to measure realized adoption or realized returns.

The decision variable is the maximum justifiable investment — the capital outlay at which the discounted stream of annual savings exactly offsets the investment over the service life. This formulation is adopted rather than the net present value of a specific commercial machine because list prices for precision-spraying systems in Kazakhstan are not publicly disclosed; computing the ceiling avoids conditioning the result on an unverifiable price assumption and yields a decision rule applicable to any machine whose price becomes known.

2.2 Reference production system

The reference system is spring wheat in the northern grain belt — the crop and region that together account for the bulk of Kazakhstan's agricultural exports. Farm sizes of 1000, 3000, 5000, 10000 and 20000 hectares were evaluated to capture the scale distribution of commercial grain enterprises.

2.3 Data sources

Sectoral and regional output data were obtained from the Bureau of National Statistics of the Republic of Kazakhstan (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of

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Kazakhstan 2024). Price and cost parameters were compiled for 2024–2026 from the following sources: wheat prices from the Eurasian Trading System (ETS) commodity exchange quotations of 1 August 2025 (Eurasian Trading System 2025); the disaggregated per-hectare cost structure and average yield from farm-level estimates published by the sectoral outlet ElDala.kz in August 2025 (ElDala.kz 2025); the official cost norm from the Ministry of Agriculture of the Republic of Kazakhstan (January 2025; Ministry of Agriculture of the Republic of Kazakhstan 2026); machinery fleet renewal rates, depreciation levels, and investment subsidy rates from Ministry of Agriculture statements of May 2026 (Ministry of Agriculture of the Republic of Kazakhstan 2026); and the concessional leasing rate from KazAgroFinance (Ministry of Agriculture of the Republic of Kazakhstan 2026). Technical performance coefficients for AI-based targeted spraying were obtained from manufacturer season summaries covering more than one million acres in 2024 (John Deere 2024) and from independent field-scale trials conducted by Iowa State University across 415 acres in the same season (Iowa State University 2024).

2.4 Scenario specification

Herbicide savings were specified as three scenarios rather than a point estimate, reflecting the documented sensitivity of the targeted application to weed pressure: a low scenario of 43.9%, a central scenario of 59% corresponding to the manufacturer's season average, and a high scenario of 76% corresponding to the independent trial average. Treating performance as a range rather than a point is methodologically necessary, since the reported field-level variation from 43.9% to 87.2% implies that the return is site-specific and cannot be assumed to be uniform.

2.5 Calculation procedure

The annual saving per hectare is the product of the baseline herbicide cost and the scenario saving rate. The total annual saving is this figure multiplied by the sown area. The maximum justifiable investment is the present value of this annuity over an eight-year service life:

$$I(max) = S \times A \times [1 - (1 + r)^{-n}] / r \quad (1)$$

where I(max) is the maximum justifiable investment, S is the annual saving per hectare, A is the sown area, r is the discount rate, and n is the service life in years. Two discount rates were applied: 6%, the documented concessional leasing rate, and 18%, an indicative commercial rate for producers without access to concessional finance. The break-even sown area for a given system price was obtained by inverting the same expression.

2.6 Assumptions and their justification

Four assumptions require statement. The eight-year service life reflects normative depreciation periods for self-propelled agricultural machinery and is conservative relative to actual service lives in Kazakhstan, which exceed normative ones. The 18% commercial rate is an assumption rather than a documented figure and is used only as a comparator to isolate the effect of financing terms. Only the herbicide channel is quantified; savings in fuel, fertilizer, and application labor, and any agronomic yield response, are excluded; thus, the estimates are lower bounds on total benefits. Finally, savings are assumed to be constant across years, which abstracts from weed-resistance dynamics that could alter the saving profile over the service life (Beckie *et al.* 2019).

3. RESULTS

3.1 The sector in aggregate and its regional structure

The gross output of agriculture, forestry, and fishing reached approximately 9.7 trillion KZT, of which crop production accounted for 60.7% (5,890 billion KZT) and livestock production for 3,800 billion KZT, with forestry (27.3 billion KZT) and fishing and aquaculture (37.1 billion KZT) contributing marginally. Therefore, crop production is the dominant component and the appropriate focus of a technology assessment.

A methodological point deserves note because published regional figures are frequently misread. The gross output of agriculture comprises three components rather than two: crop production, livestock production, and services in the field of agriculture. In the 2021 accounts, for example, crop output of 4,232,458.6 million KZT and livestock output of 3 104,507.7 million KZT sum to 7,336 966.3 million KZT against a reported total of 7,346,672.6 million

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KZT; the residual of 9,706.3 million KZT is the services component, not a data error. Studies that compare only the two production components with the headline total will therefore report a spurious discrepancy.
The output is regionally concentrated. Table 1 reports the shares of the leading regions in national gross agricultural output and crop output.

Table 1. Regional structure of gross agricultural output, Republic of Kazakhstan, 2023

Region	Share of gross agricultural output (%)	Share of crop output (%)
Turkestan	12.7	14.0
North Kazakhstan	10.0	12.7
Almaty	9.2	n/a
Akmola	9.2	8.7
Kostanay	n/a	11.0
Four leading regions, combined	41.1	—

Note: compiled by the author from data of the Bureau of National Statistics of the Republic of Kazakhstan. The shares for the Almaty region in crop output and for the Kostanay region in total output were not separately reported in the source publication.

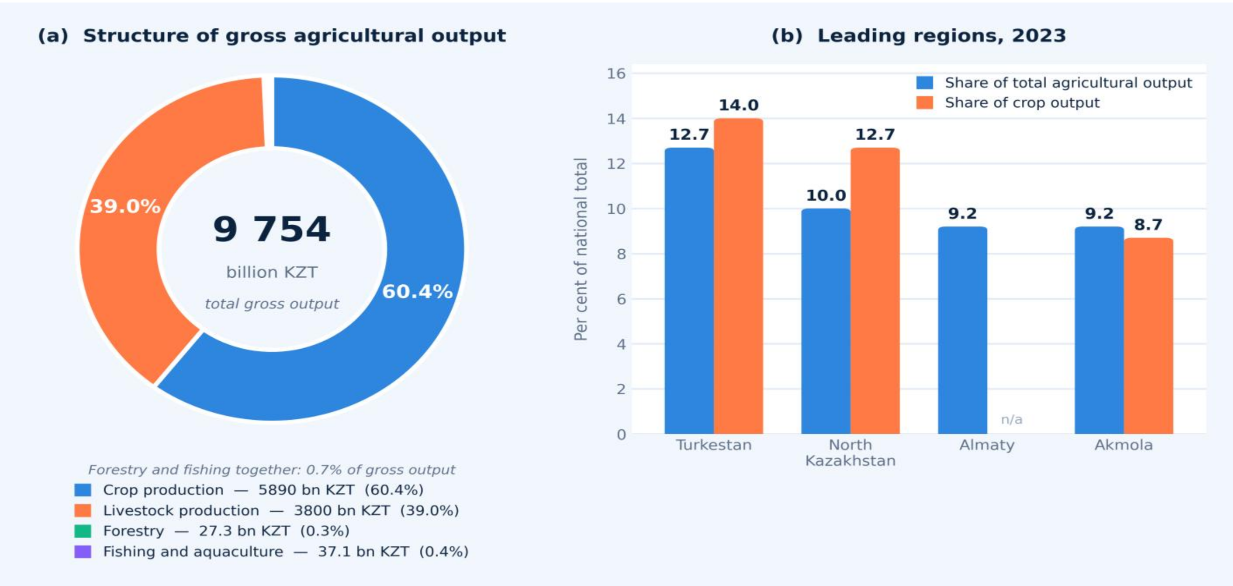

Fig. 1. Structure of gross agricultural output and shares of the leading regions, Republic of Kazakhstan.

The concentration of crop output in the northern grain belt — North Kazakhstan, Akmola, and Kostanay regions — defines the population to which the subsequent analysis applies. These are extensive spring-wheat systems with large field sizes, and it is in these systems that the cost structure examined below prevails.

3.2 The baseline: cost structure and margin position

Any assessment of agricultural innovation must begin with the cost structure it is meant to change. Table 2 reports the parameters of the reference production system — spring wheat in the northern grain belt, the crop and region that together account for the bulk of Kazakhstan's agricultural exports.

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Table 2. Parameters of the reference production system, Northern Kazakhstan, 2025.

Parameter	Value	Source
Average wheat yield	12 c ha^{-1} (1.2 ton ha^{-1})	ElDala.kz, August 2025
Wheat price, class 4	87 000 KZT ton^{-1}	ETS exchange, 01.08.2025
Wheat price, class 3 (ordinary)	97 000 KZT ton^{-1}	ETS exchange, 01.08.2025
Wheat price, hi-pro (30% gluten)	125 000 KZT ton^{-1}	ETS exchange, 01.08.2025
Total production cost	~100 000 KZT ha^{-1}	ElDala.kz, 2025
Ministry of Agriculture cost norm	116 000 KZT ha^{-1}	MoA RK, January 2025
Fleet renewal rate, 2025	6.5%	MoA RK, May 2026
Fleet renewal target, 2026	8.0%	MoA RK, May 2026
Average fleet depreciation	76% (tractors 80%)	MoA RK
Preferential leasing rate	6% per annum	KazAgroFinance
Investment subsidy, domestic machinery	30% of cost	MoA RK, 2026
Investment subsidy, imported machinery	15–25% of cost	MoA RK, 2026
Concessional field-work lending, 2025	700 bn KZT	Agrarian Credit Corp.

Note: Compiled by the author from official and market sources.

The disaggregated cost structure is presented in Fig. 2. Seed accounts for 15000 KZT ha^{-1}, herbicides for 20,000 KZT ha^{-1} applied in two passes, fuel and lubricants for 25,000 KZT ha^{-1}, and repairs and spare parts for 10,000 KZT ha^{-1}; the residual 30,000 KZT ha^{-1} covers fertilizer, labor, credit servicing, and overheads.

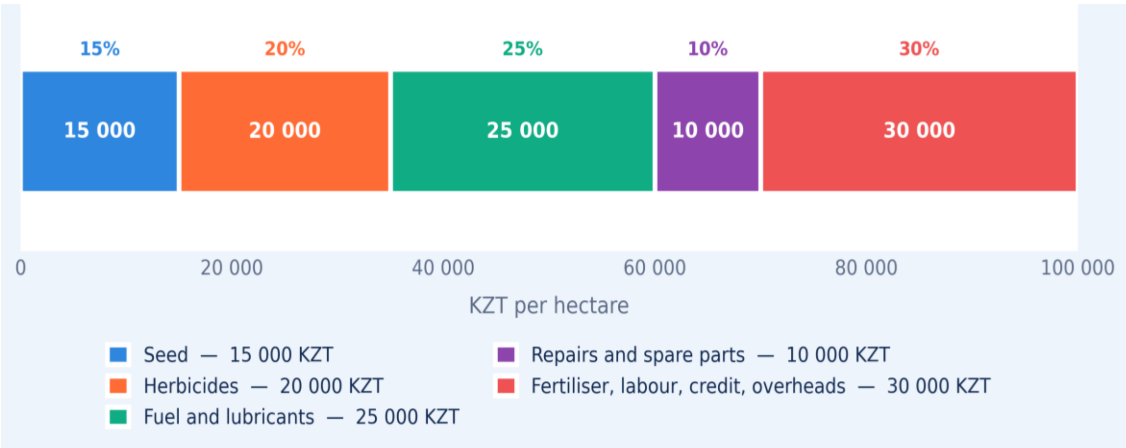

Fig. 2. Cost structure of spring wheat production, Northern Kazakhstan, 2025.

The economic significance of this structure becomes visible when it is set against revenue. Table 3 shows the gross margin under alternative yield-price combinations.

Table 3. Gross margin of spring wheat production under alternative yield and price scenarios (KZT ha^{-1}).

Yield	Revenue at 87 000	Margin at 87 000	Revenue at 97 000	Margin at 97 000
12 c/ha (national average)	104 400	+4 400	116 400	+16 400
16 c/ha	139 200	+39 200	155 200	+55 200
20 c/ha (favourable season)	174 000	+74 000	194 000	+94 000

Note: Total production cost was assumed to be 100, 000 KZT/ha. Calculated by the author.

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At the national average yield of 12 c ha^{-1} and the class-4 price prevailing in August 2025, the producer clears 4 400 KZT ha^{-1} – a margin of 4.4% on costs, which is within the error of the cost estimate itself. Therefore, the sector operates at approximately zero economic profit in an average year, and the entire margin is generated in the tail of the yield distribution. This finding reframes the question of innovation. A producer operating at a 4% margin cannot finance experimentation from retained earnings, cannot absorb the risk of a failed technology trial, and will rationally reject any investment whose payback is uncertain; however, attractive that investment appears in a technical assessment. The observed slow diffusion of advanced technologies in Kazakhstani agriculture is thus not evidence of managerial conservatism; rather, it is a predictable consequence of the margin structure.

3.3 The input-substitution channel

The cost structure identifies where automation can and cannot pay. Labor does not appear as a separate large item in extensive Kazakhstani grain production, which means that the labor-displacement rationale dominating the international robotics literature – derived largely from labor-intensive horticulture – transfers poorly to this system. The two substantial variable items amenable to precision targeting are herbicides (20 000 KZT ha^{-1}) and fuel (25000 KZT ha^{-1}). Of these, herbicides are the item for which quantified performance data from AI-based targeted applications are available.

Published field evidence provides three scenario bounds. Manufacturer data covering more than one million acres in the 2024 season report an average herbicide saving of 59% relative to broadcast application. Independent field-scale trials conducted by Iowa State University across 415 acres report an average product saving of 76%, with individual fields ranging from 43.9% to 87.2% depending on weed pressure. We therefore adopt 43.9%, 59%, and 76% as the low, central, and high scenarios. Table 4 translates these into Kazakhstani cost terms.

Table 4. Herbicide saving from AI-based targeted spraying under Kazakhstani cost conditions.

Scenario	Saving (%)	Saving (KZT ha^{-1})	Share of total cost	Yield equivalent
Low (high weed pressure)	43.9	8 780	8.8%	1.01 c ha^{-1} (+8.4%)
Central (manufacturer average)	59.0	11 800	11.8%	1.36 c ha^{-1} (+11.3%)
High (independent trial average)	76.0	15 200	15.2%	1.75 c ha^{-1} (+14.6%)

Note: *Yield* equivalent calculated at a wheat price of 87 000 KZT ton^{-1} against a base yield of 12 c ha^{-1}.

The final column expresses the saving in the unit in which Kazakhstani producers habitually think (centners per hectare). Under the central scenario, targeted spraying delivers a cost reduction economically equivalent to raising yield by 1.36 c ha^{-1}, or 11.3% above the national average, with no agronomic change, no additional water, and no genetic improvement. Set against the 4400 KZT ha^{-1} margin computed in Table 3, the same saving is 2.7 times the entire gross margin of an average season. This is the central quantitative result of the analysis: in a low-margin extensive system, input-targeting technologies do not marginally improve profitability – they determine whether profitability exists at all.

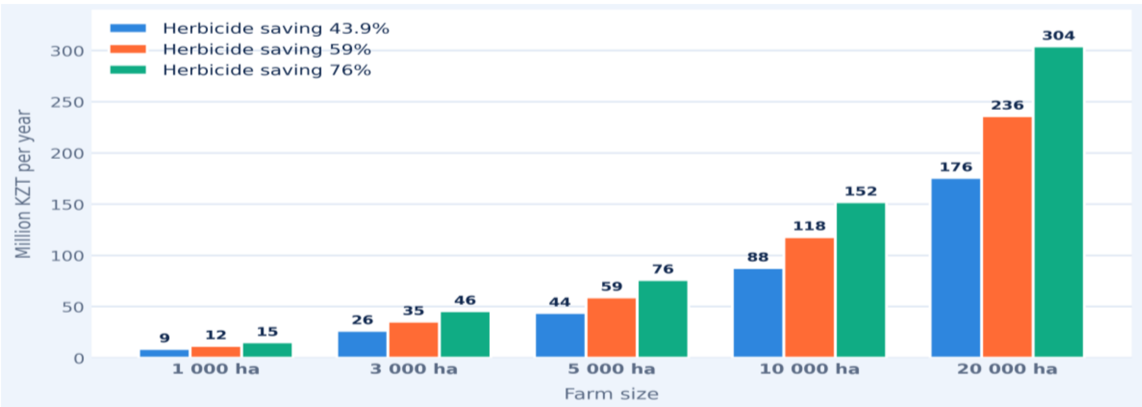

Fig. 3. Annual herbicide cost saving from AI-based targeted spraying, by farm size.

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3.4 Scale dependence and the investment ceiling

Because the saving accrues per hectare while the technology is acquired as an indivisible unit, profitability is governed by farm size. Fig. 3 shows annual savings by farm size and scenario.

Annual savings range from 8.8 million KZT on a 1000-hectare farm under the low scenario to 304 million KZT on a 20000-hectare farm under the high scenario. Capitalizing these flows over an eight-year service life yields the maximum investment a producer can justify (Table 5). Two discount rates are applied: 6%, the preferential leasing rate available through KazAgroFinance, and 18%, an indicative commercial rate for producers who do not access concessional finance.

Table 5. Maximum justifiable investment in a precision-spraying system, million KZT, 8-year horizon.

Savings scenario	1,000 ha	3,000 ha	5,000 ha	10,000 ha	20,000 ha
At 6% — preferential leasing					
Saving 43.9%	54.5	163.6	272.6	545.2	1 090.4
Saving 59%	73.3	219.8	366.4	732.8	1 465.5
Saving 76%	94.4	283.2	471.9	943.9	1 887.8
At 18% — commercial credit					
Saving 43.9%	35.8	107.4	179.0	358.0	716.0
Saving 59%	48.1	144.3	240.6	481.2	962.3
Saving 76%	62.0	185.9	309.9	619.8	1 239.6

Note: Present value of an 8-year annuity of annual herbicide savings. Calculated by the author.

The results quantify the finding that the descriptive literature on agricultural digitalization states only qualitatively. Moving from commercial to preferential finance raises the investment ceiling by 52% at every farm size and savings scenario – an effect larger than the entire difference between the low and central technical performance scenarios. The cost of capital, not the technical capability of the machine, is the binding constraint on adoption. A producer with 5000 hectares can justify 366 million KZT of investment at 6% but only 241 million KZT at 18%; the 126-million-KZT difference is created by the financing terms alone. This has a direct policy implication: extending concessional leasing coverage is a more powerful adoption instrument than subsidizing the equipment purchase price, and it is fiscally cheaper per hectare of adoption induced.

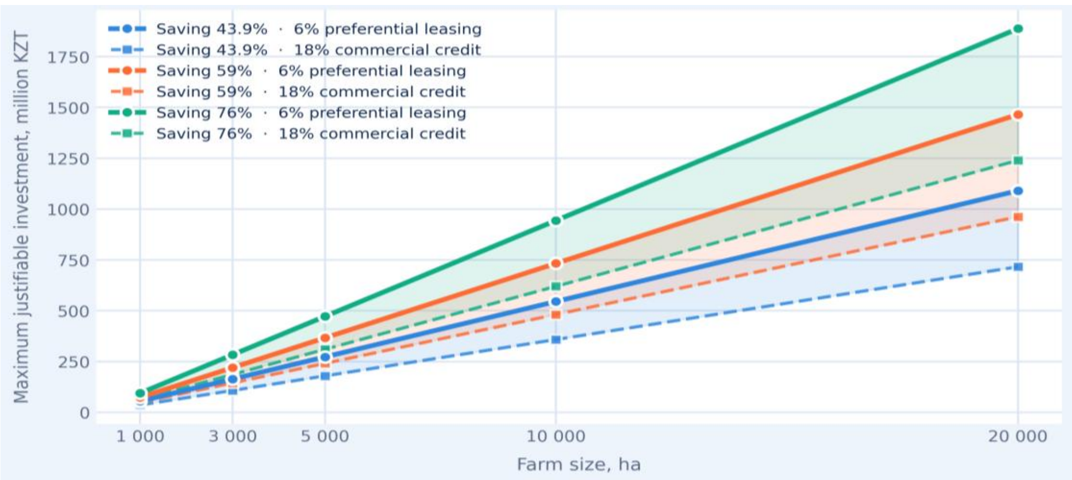

Fig. 4. Investment ceiling at which the technology breaks even over an 8-year horizon.

The investment subsidy nonetheless compounds this effect. With the 30% reimbursement available for domestically produced machinery, the ceiling on list price rises by a factor of 1.43; with the 15–25% band applicable to imported equipment, by 1.18 to 1.33. Since AI-based spraying systems are not currently

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manufactured in Kazakhstan, the differentiated subsidy regime – introduced to support domestic machinery producers — operates as an implicit tax on precisely the technology class with the highest measured input-saving potential.

3.5 The break-even farm size

Inverting the calculation yields the operational decision rule (Fig. 5, Table 6).

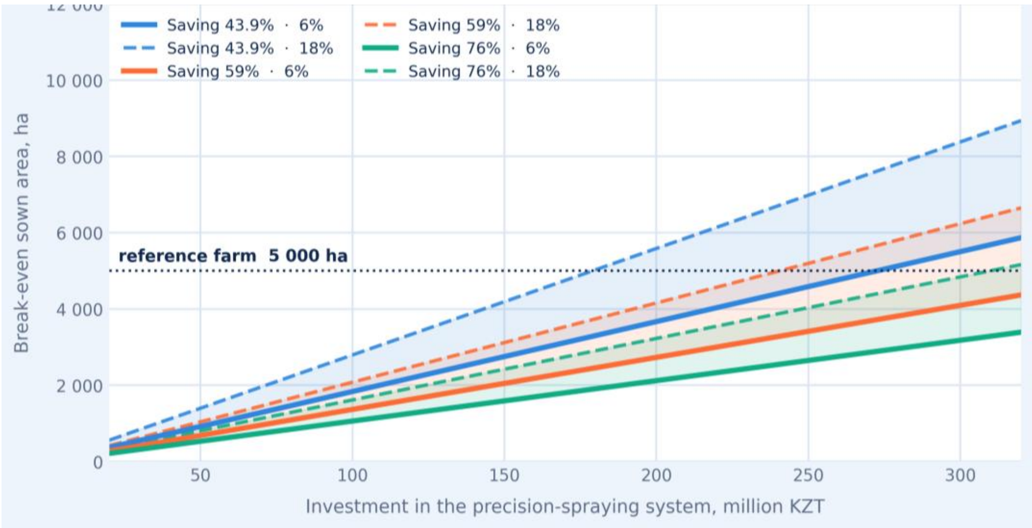

Fig. 5. Minimum farm size at which targeted spraying is economically justified.

Table 6. Break-even sown area under the central savings scenario (59%), hectares.

System investment	At 6% (preferential)	At 18% (commercial)
50 million KZT	682	1 039
100 million KZT	1 365	2 078
150 million KZT	2 047	3 118
200 million KZT	2 729	4 157
300 million KZT	4 094	6 235

Note: Calculated by the author for an 8-year service life.

At preferential rates, a system costing 200 million KZT is justified from 2729 hectares; at commercial rates, the same system requires 4157 hectares. Therefore, the threshold is located squarely within the size distribution of Kazakhstani grain enterprises rather than at its extreme upper tail, which means that the technology is relevant to a substantial share of the northern grain belt, but it is emphatically not relevant to peasant farms and household plots that constitute the majority of agricultural units by number. Any national program built on individual machine ownership will therefore reach a minority of producers. The corollary is that the diffusion pathway for small and medium producers runs through service provision – contract spraying, machinery rings, and cooperative ownership – rather than through purchase subsidies, since these arrangements convert an indivisible capital good into a per-hectare variable cost and remove the scale threshold entirely.

3.6 Robotization versus fleet renewal

The preceding results must be read against the physical state of the capital stock. The average depreciation of the self-propelled machinery fleet stands at 76%, reaching 80% for tractors, and the renewal rate reaches 6.5% in 2025 against a target of 8% – an improvement on the 4.5% recorded earlier, but still leaving actual service lives well beyond normative ones. A fleet in this condition constrains the adoption of AI-based systems in a way that is easy to overlook: targeted spraying requires a carrier machine with functioning boom-height control, section control, and compatible electronics. Retrofitting such systems onto equipment already at 76% depreciation is technically marginal and economically unattractive.

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This generates a sequencing conclusion that runs against the intuition of technology-led strategies. The returns computed in Table 4 are conditional on the existence of serviceable carrier platforms. Where that platform is absent, the first-best use of the marginal investment tenge is fleet renewal, and the AI system is justified only in the subsequent investment cycle. Robotization and mechanization are complements in sequence, not substitutes in choice. A program that funds the former while the latter remains unresolved will generate low realized returns and discredit the technology among producers.

4. DISCUSSION

The results confirm the central proposition of the economics of agricultural automation – that profitability is scenario-dependent rather than general (Lowenberg-DeBoer *et al.* 2020) – while identifying a mechanism specific to extensive dryland systems. In the international literature, the dominant rationale for automation is labor displacement, derived largely from labor-intensive horticulture. In Kazakhstani grain production, labor is not a large separable cost item, and returns arise instead from input substitution. Therefore, the technologies worth prioritizing are those acting on variable inputs, not those replacing field operators, a reading consistent with whole-farm analyses showing that the case for autonomous equipment rests on economies of size and relative factor prices rather than technical capability alone (Lowenberg-DeBoer *et al.* 2021).

The identification of the cost of capital as the binding constraint connects this study to the literature on institutions in transition agriculture. The concessional finance raises the justifiable investment by more than the entire range of technical performance uncertainty is an empirical counterpart to the finding that Kazakhstan's land reform failed to make land usable as collateral, leaving credit rationed for precisely the medium-sized producers most likely to adopt scale-neutral technologies (Kvartiuk & Petrick 2021). It also refines the established result that subsidies are negatively associated with technical efficiency (Tleubayev *et al.* 2022; Mamun 2024): the present analysis suggests that the problem lies less in the existence of support than in its form, since transfers linked to output or purchase price weaken incentives whereas concessional financing relaxes a genuine constraint without guaranteeing income independently of performance.

The near-zero margin documented in Section 3.2 offers an economic explanation for a phenomenon usually attributed to behavioral factors. Regional studies of agricultural digitalization frequently conclude that adoption is impeded by insufficient awareness or conservatism and report weak or negative measured effects of digital literacy and rural connectivity (Dauliyeva 2022; Bekbossinova & Doszhan 2025). The margin structure provides a simpler account fully consistent with the classical adoption framework, in which risk aversion and credit access are primary determinants (Feder *et al.* 1985): a producer earning 4% cannot self-finance experimentation or absorb the downside of a failed trial. On this reading, information campaigns will underperform relative to instruments that reduce financial exposure, a conclusion also supported by evidence on the role of peer networks and demonstrated experience in shaping technology valuations (Blasch *et al.* 2022). Digitalization in this sector is therefore better understood as a complement to capital renewal rather than an independent driver of productivity (Şengül *et al.* 2025).

The sequencing conclusion of Section 3.6 qualifies the technology-led strategies prevailing in regional policy discussions. Where the carrier platform is absent, funding automation ahead of mechanization will generate low realized returns. This complements evidence that capital scarcity rather than technology availability constrains Kazakhstani agriculture (Kurmanova 2022; OECD 2025), and it implies an ordering of expenditure that current programme design does not reflect.

Finally, the scale threshold has distributional implications for the study. Because the break-even area excludes the majority of agricultural units by number, purchase-based instruments will concentrate benefits among large enterprises, reproducing the allocation skew already documented in assessments of Kazakhstani state support (Kazhiyeva & Zhailaubayeva 2022; Alipbeki 2024; Siximbayeva *et al.* 2025). Service provision offers a route around the indivisibility of capital goods and merits explicit policy attention (Mottaleb *et al.* 2017), particularly given projections of declining wheat yields that raise the value of input efficiency (World Bank 2024; Tleubayev & Syzdykov 2025).

5. CONCLUSION

This study assessed which agricultural innovations are economically justified under Kazakhstani factor prices and financing conditions. Four conclusions are as follow.

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Spring wheat production in the northern grain belt operates at approximately zero economic profit in an average season, clearing 4,400 KZT ha^{-1} at a yield of 12 c ha^{-1} and a price of 87,000 KZT ton^{-1}. Profitability is generated almost entirely in the upper tail of the yield distribution, which explains the observed reluctance to invest in unproven technology without recourse to behavioral explanations.

AI-based targeted spraying reduces herbicide expenditure by 8,780 to 15,200 KZT ha^{-1} – equivalent to raising yield by 1.0 to 1.75 c ha^{-1} and two to three times the average gross margin. The economic mechanism is input substitution rather than labor displacement, which implies that technologies acting on variable inputs should be prioritized over those replacing operators.

The binding constraint on adoption is the capital cost. Concessional financing raises the maximum justifiable investment by 52%, an effect that exceeds the entire range of technical performance uncertainty. Broadening access to concessional leasing is therefore a more effective and fiscally cheaper instrument than raising purchase subsidies, while the current differentiated subsidy regime operates as an implicit tax on the technology class with the highest input-saving potential.

Adoption is scale-dependent, with a break-even area between approximately 1,400 and 4,200 hectares. For producers below this threshold, the viable pathway is service provision rather than ownership. Where the machinery fleet remains at high depreciation, fleet renewal should precede automation: the two are complements in sequence rather than competing alternatives.

Three limitations qualify these results. The technical coefficients are transferred from trials conducted on row crops in North American conditions; weed spectrum, weed pressure and canopy structure in Kazakhstani spring wheat differ, and the realized saving may lie outside the adopted range in either direction. Local field validation is a necessary next step and cannot be substituted by transferred parameters. Second, the analysis captures only the herbicide channel and therefore understates total benefits, omitting potential savings in fuel, fertilizer and application labor as well as any agronomic yield response. Third, the discount rates are indicative: the 6% preferential rate is documented, whereas the 18% commercial rate is an assumption, and adoption decisions in practice depend on the producer's actual, frequently rationed, access to credit – a constraint that the literature on Kazakhstani land and credit markets identifies as structural rather than transitory.

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Author contributions

Conceptualisation and methodology — M.B.A. and O.A.A.; data curation and formal analysis — M.B.A.; writing of the original draft — M.B.A.; review and editing — O.A.A., G.S.S. and S.V.; supervision — O.A.A. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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