

The adaptability of seed drills in modern crop production technologies

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Abstract. The relevance of this study stems from the fact that the transition of farms from traditional tillage to minimum and no-till techniques requires seed drills capable of operating consistently under varying conditions of crop residue, soil moisture and field micro-relief. A lack of alignment between the design of the seed drill and the cultivation technology leads to uneven seed placement, excessive fuel consumption and increased costs for renewing the machinery and tractor fleet. The aim of the study was to substantiate the adaptability of modern monoblock, modular and combined seed drills and to assess the feasibility of using a direct-drilling tillage attachment (DDTA) with standard grain seed drills. The research methodology involved a comparative structural and technological analysis of sowing units based on standardised criteria, the standardisation of indicators on a 0-1 scale, multi-criteria ranking and verification of the stability of results when weighting coefficients were altered. The working parts, working width, row spacing, traction requirements, suitability for use in conventional, minimum and direct drilling, as well as the conditions under which the shortcomings of individual designs became critical, were analysed. The statistical analysis included the determination of the mean, sample standard deviation, coefficient of variation and Spearman's rank correlation. The result obtained characterises the preliminary comparative suitability according to the adopted system of criteria and does not constitute proof of the absolute technical superiority of the DDTA without field testing of reliability, durability and service life. It was established

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that the highest versatility was provided by units with a separate soil-tilling section and a sowing module, as they combined the preparation of the sowing strip with the possibility of using the seed drill separately. The theoretical analysis showed that the DDTA variant with a standard seed drill fell into the group of Pareto-efficient solutions due to its better affordability, adjustable row spacing and suitability for upgrading existing machinery. At the same time, complex European sowing units had the advantage in terms of depth stability and technical equipment, but required greater tractor power and higher capital expenditure

Keywords: no-till; minimum tillage; coulter; seed drill; crop residues; resource conservation; multi-criteria optimisation

INTRODUCTION

Sowing has always been, and remains, the stage at which a technical error directly results in a loss of plant density, uneven plant development and reduced yields; therefore, ensuring high-quality sowing of crops, regardless of the tillage method used, is one of the key factors in the efficiency of modern agriculture. Under current conditions, the problem is compounded by the fact that a single farm often combines traditional soil preparation, minimum and strip tillage, as well as direct drilling, whilst seed drills of various designs frequently demonstrate limited versatility: some are effective on a levelled seedbed following cultivation but lose depth consistency on stubble with a large amount of crop residue, whilst others, designed for no-till technology, are not always economically viable for small and medium-sized farms. This complicates the choice of machinery, as it is necessary to take into account not only the machine's productivity but also the limits of its adaptability to soil conditions, tillage techniques, the level of energy supply and the farm's financial capabilities. In this regard, there is a need for a scientifically grounded analysis of modern seed drill designs to determine their capabilities and limitations, as well as to select a sowing unit capable of ensuring the required sowing quality under various operational conditions without an unjustified increase in capital and operating costs.

Researchers Y. Ma *et al.* (2025) examined the development of direct-drilling technologies in conservation tillage systems and concluded that the key factor in their effectiveness was the ability of the working parts to cut through or deflect crop residues without causing excessive soil disturbance. This study confirmed that the adaptability of a seed drill should be assessed not only by the type of coulter, but also by the coulter's compatibility with the skimmers, the ground-following system and the operating modes. Researchers G. Raveendran *et al.* (2025) systematised mechanised solutions for the precision sowing of small-seeded crops and emphasised the interrelationship between metering quality, furrow stability and the design of the seed tube. Their results showed that the versatility of a sowing unit is

limited not only by the tillage section but also by the sowing system's ability to maintain a uniform seed flow at different speeds.

Researchers S. Wang *et al.* (2024) investigated the sowing depth control system of high-speed precision seeders based on the fusion of data from several sensors. The authors found that section variations and the micro-relief of the field significantly affected depth error; therefore, modern designs required not only robust working parts but also mechanisms to control the downforce. This finding was taken into account when introducing the depth stability criterion. Researchers W. Liu *et al.* (2025) summarised the key technologies of intelligent grain seeders and demonstrated that the development of sowing technology is shifting towards active regulation of the sowing rate, seed position control and automatic adjustment of working parts. For Ukrainian conditions, these solutions are not yet always economically viable; however, they provide a benchmark for assessing the technological potential of modular seeding units.

Ukrainian researchers A. Nanka *et al.* (2021) substantiated the presence and parameters of guide elements in coulters that improved seeding quality and crop yield. They demonstrated that even a relatively minor design modification within the coulter could reduce seed scattering in the furrow; therefore, when selecting a seed drill, it is important to consider not only the overall machine layout. Researchers E.B. Aliiev *et al.* (2024) conducted tests on an improved seed delivery system for a pneumatic seed drill and found that elements for slowing down and stabilising the seed flow are particularly important under no-till conditions with a high concentration of crop residues. This study confirmed the need to view the seed drill as an integrated system in which the tillage module, coulter and seed delivery system mutually determine the quality of performance. Researchers V. Shebanin *et al.* (2025) assessed the economic efficiency of growing winter wheat using the resource-saving Mzuri-ProTil technology and demonstrated that integrating tillage, sowing and the

application of materials into a single pass can improve economic performance. This is important for justifying a shift from describing expensive sowing complexes to analysing more affordable solutions for modernising existing seed drills.

Researcher P.V. Lykhovyd (2024) analysed the biological activity of Ukrainian soils under various tillage methods and highlighted the mixed results of no-till farming across different soil and climatic conditions. This conclusion emphasised that the choice of seed drill cannot be universal for all regions; it must take into account the soil texture, moisture supply, previous crop and the level of crop residues. Researchers V. Zadorozhnyi *et al.* (2025) investigated weed control in no-till soya cultivation in the Right-Bank Forest-Steppe of Ukraine and demonstrated that fuel and cost savings are accompanied by the need for enhanced weed management. Thus, a direct-drilling seed drill must be evaluated in terms of its technological implications, crop residue retention, the possibility of early sowing, the need for herbicides and its ability to form a seedbed without excessive soil disturbance. Researchers U. Sultan *et al.* (2023) developed a multi-crop, energy-efficient seed drill and demonstrated the potential of compact machines designed to reduce energy consumption. In the context of this study, this confirmed the value of evaluating not only large-scale sowing systems but also simpler units capable of delivering acceptable sowing quality with a lower tractor power requirement.

The analysis of the studies reviewed above showed that the literature has devoted considerable attention to individual working elements, sensor-based depth control, the economics of resource-saving technologies and the effects of No-till on soil. However, the adaptability of different seed drill configurations (monoblock, modular and combined) for farms that simultaneously use conventional, minimum-tillage and direct-drilling systems has not been sufficiently compared. There is also insufficient justification of the conditions under which modernising a standard grain seed drill with a soil-working attachment can serve as an alternative to purchasing a complex seeding system. The aim of this study was to conduct a design and technological analysis of modern seed drills, determine their advantages and limitations under different crop production systems, and validate a multi-objective model for selecting a seeding unit in order to substantiate the feasibility of using a direct-drilling tillage attachment (DDTA).

MATERIALS AND METHODS

The study was conducted as a comparative design and technological analysis of continuous-row seed drills

that can be used for conventional, minimum-tillage and direct drilling. The analysed units included monoblock, modular and combined seed drills: Farmet Falcon 6 PRO Tandem, HORSCH Sprinter ST, Farmet Falcon Compact, Väderstad Rapid 300-400C/S, BEDNAR OMEGA OO_FL, ALFA 4/6 No-Till, a Great Plains unit with a CPH soil-preparation attachment, GREEN PLAINS 1500, and the proposed option of using a DDTA with a standard grain seed drill. The sample included machines for which technical specifications were available regarding working width, row spacing, type of working elements, tractor power requirements and intended application. The information base consisted of manufacturers' technical materials, scientific publications on seed drills and working elements, and design data for the proposed DDTA. For each machine, the following parameters were determined: machine layout; presence of a separate soil-working section; type of coulters and cutting discs; method of following field microrelief; working width; row spacing; possibility of simultaneous fertiliser application; suitability for conventional, minimum-tillage and direct drilling; relative energy requirements; and potential service complexity. Values that did not have common physical units were normalised on a scale from 0 to 1, where 1 represented the best performance against the criterion among the compared solutions.

The proposed DDTA was considered as a separate trailed soil-working section attached to a tractor and coupled with a standard grain seed drill. The design provides a working width of 3.6, 5.4 or 6.0 m, with vertically arranged corrugated discs as the working elements, a basic row spacing of 15 cm and the possibility of adjusting it. Depending on the working width of the seed drill, tractor power of 80-170 hp is recommended. The DDTA was assessed using the same system of criteria and the same normalisation procedure as the standard seeding units. The input data for the DDTA consisted of its design parameters, machine layout and stated technological capabilities; field-test results were not included in the calculation matrix. The seed drills were classified according to the layout of their working elements into monoblock machines, in which soil-working and seeding elements are mounted on a common frame; block-modular machines, in which separate sections perform seedbed preparation and seeding; and combined units, in which a standard seed drill is attached to a separate soil-working attachment. According to the nature of soil preparation, the units were classified as systems for full-width preparation, strip preparation and direct furrow formation. According to the type of working element, tine, disc, turbo-disc and combined systems were compared.

To reduce subjectivity in the comparison, a multi-objective selection model was used. It made it possible to link the design characteristics with a quantitative assessment of adaptability. The objective functions were formulated to minimise costs, maximise agronomic performance, minimise soil impact and minimise the number of machines purchased.

The function for minimising the total cost of the unit:

$$J_1 = \sum_i c_i^{cap} x_i + \sum_f \sum_i c_{i,t,f}^{op} S_{fyi,f} \quad (1)$$

where c_i^{cap} – capital expenditure on the purchase of a unit of machinery i ; x_i – number of units of machinery type i ; $c_{i,t,f}^{op}$ – specific operating costs (fuel, maintenance, wages, etc.) for machinery i during period t on field f ; S_f – area of field f ; $Y_{i,f}$ – a binary variable (1 – the piece of machinery is used on field f , 0 – no).

Function for maximising the agronomic quality of field work:

$$J_2 = \sum_f \sum_i q_{i,t,f} S_{fyi,f} \rightarrow \max, \quad (2)$$

where $q_{i,t,f}$ – an indicator of the agronomic quality of work carried out by machine i during period t on field f .

The function minimises the impact on the soil:

$$J_3 = \sum_f \sum_i d_{i,t,f} S_{fyi,f} \quad (3)$$

where $d_{i,t,f}$ – the coefficient of the impact of machinery i on the soil (compaction, erosion processes, etc.) during the period t on field f .

The objective function is to minimise the number of units of machinery purchased:

$$J_4 = \sum_i x_i \quad (4)$$

where x_i – the number of units of equipment of type i purchased.

The quantitative indicators were normalised using the min-max method. For incentive and disincentive criteria, the following relationships were applied respectively:

$$z_{ij} = (x_{ij} - x_{j, \min}) / (x_{j, \max} - x_{j, \min}); \quad (5)$$

$$z_{ij} = (x_{j, \max} - x_{ij}) / (x_{j, \max} - x_{j, \min}). \quad (6)$$

For qualitative characteristics, a standardised 0-1 scale with increments of 0.05 was used, based on pre-defined descriptive levels. A value of 1 corresponded to the best fulfilment of the criterion amongst the alternatives under comparison, whilst a value of 0 indicated the absence of the relevant functional

property. The integrated indicator was calculated as a weighted sum:

$$A_i = 0.20T_i + 0.15R_i + 0.20D_i + 0.15M_i + 0.15E_i + 0.15U_i. \quad (7)$$

Higher weights were assigned to criteria T and D (0.20 each) due to their direct impact on the machine's operational compatibility and the uniformity of seed placement; the other criteria were assigned equal weights of 0.15. Reliability, durability, actual service life and sowing accuracy at higher speeds were not included as independent criteria due to the lack of comparable field test results for all machines. Thus, A_i characterises preliminary comparative suitability within the accepted system of criteria, rather than the absolute technical superiority of the seeding unit.

For a set of $n=9$ integrated assessments, the mean, sample standard deviation and coefficient of variation were calculated:

$$\bar{A} = \left(\frac{1}{n}\right) \cdot \sum A_i; \quad (8)$$

$$s = \sqrt{\left[\frac{\sum (A_i - \bar{A})^2}{n-1}\right]}; \quad (9)$$

$$CV = \left(\frac{s}{\bar{A}}\right) \cdot 100\%. \quad (10)$$

The stability of the ranking was tested using the Monte Carlo method over 1,000 iterations. In each iteration, each base weight was independently varied within a range of $\pm 10\%$, after which the weights were re-normalised to sum to 1, new values of A_i were calculated, and ranks were assigned; in the event of tied scores, the average rank was used. The similarity between the baseline and modified rankings was assessed using Spearman's rank correlation coefficient:

$$\rho_s = 1 - \left[\frac{6 \sum d_i^2}{n(n^2-1)}\right]. \quad (11)$$

The table matrix of initial ratings was created in Microsoft Excel. Automated normalisation, the calculation of A_i , descriptive statistics, 1,000 sensitivity scenarios and Spearman's coefficients were performed in Python 3.13. Thus, the software environment was used directly to obtain quantitative results. To verify this logic, a computational validation of the integral adaptability index was carried out. Scores ranging from 0 to 1 were assigned based on the technical characteristics, design features and technological capabilities of the units. The index should not be interpreted as a test result; it reflects comparative engineering suitability according to the accepted criteria. The A_i index is used as a tool for preliminary engineering selection and does not replace field tests for reliability, durability,

sowing accuracy and the service life of the machines. The weights were selected taking into account that technological versatility and depth stability are of the greatest importance for seedling quality. The sensitivity of the result was verified by varying each weight by $\pm 10\%$, followed by normalising the sum of the weights to one. Data processing was carried out in Microsoft Excel, with verification calculations performed in Python 3.13. The results are presented in the form of comparative tables and a ranking of alternatives.

RESULTS AND DISCUSSION

A comparison of the seed drills showed that their adaptability was determined not by a single parameter, but by a combination of layout, type of working body, surface tracking and traction power requirements. Thus, the

technical characteristics of the machines under analysis were first summarised according to common criteria (Table 1). This made it possible to move from a descriptive list of models to a comparison of their suitability for different operational scenarios. Based on the results of the classification of working body configurations, the units were grouped into three design categories: integrated monoblock or anchor systems (Falcon 6 PRO Tandem, HORSCH Sprinter ST, ALFA No-Till); modular multifunctional units (Falcon Compact, Rapid 300-400C/S, BEDNAR OMEGA OO_FL); and combined units with a separate tillage attachment and a base seed drill (Great Plains CPH + drill, GREEN PLAINS 1500, DDTA + standard grain seed drill). This grouping has been used in the subsequent comparison of advantages, critical operating conditions and integral index values.

Table 1. Standardised comparison of the analysed seeding units

Seeding unit	Configuration	Working elements	Width, m	Row spacing, cm	Tractor power	Rational application
Falcon 6 PRO Tandem	monoblock/modular	anchor-type coulters, rollers	6	20-25	approximately 200 hp and above	minimum-tillage and direct drilling on fields with moderate amounts of crop residues
HORSCH Sprinter ST	monoblock anchor-type	Duett anchor-type coulters / cultivator principle	4-6	25-32	120-230 hp	mulched, direct drilling and sowing after ploughing
Falcon Compact	modular	disc tillage section and disc coulters	3-6	12.5-16.7	120-180 hp	conventional, minimum-tillage and stubble drilling
Rapid 300-400C/S	combined	disc section, disc coulters, rollers	3-4	12.5	90-130 hp	versatile operation following different soil preparation methods
BEDNAR OMEGA OO_FL	universal system	PROFI/TURBO coulters, disc section, disc coulters	4-9	12.5 or 16.7	180-500 hp	large areas, high-productivity technologies with fertiliser application
ALFA 4/6 No-Till	monoblock seed drill with attachment	turbo discs and disc coulters	4 or 6	20	from 100-120 hp	direct drilling of cereals with moderate capital expenditure
Great Plains CPH + drill	combined	vertical cutting-disc for the attachment and grain seed drill	3.66-6.10	18-20.25	85-250 hp	No-till and separate use of the seed drill in prepared soil
GREEN PLAINS 1500	combined	vertical cutting-disc for the attachment and disc coulters	4.6	1.8	from 120 hp	affordable stubble drilling of cereals and legumes
DDTA + standard grain seed drill	separate attachment + base seed drill	vertical corrugated discs, variable row spacing	3.6; 5.4; 6.0	15 with adjustable options	depending on the base seed drill (80-170 hp)	modernisation of the existing machinery fleet for minimum-tillage and direct drilling

Source: compiled by the authors based on research

Table 1 shows that universal systems provide a wider range of technological functions and greater operational stability, but require greater tractor power and substantial capital investment. The combined solutions from Great Plains, GREEN PLAINS and DDTA retain the option of using the base seed drill separately, while the DDTA option is additionally distinguished by adjustable working width and the

ability to adapt the row spacing to the existing machine. Monoblock tine seed drills, such as the Falcon 6 PRO Tandem (Fig. 1) and HORSCH Sprinter ST, as well as other machines of this design, have the advantage of manoeuvrability and a relatively simple kinematic arrangement. They are most suitable for fields with relatively even microrelief and a moderate layer of crop residues.

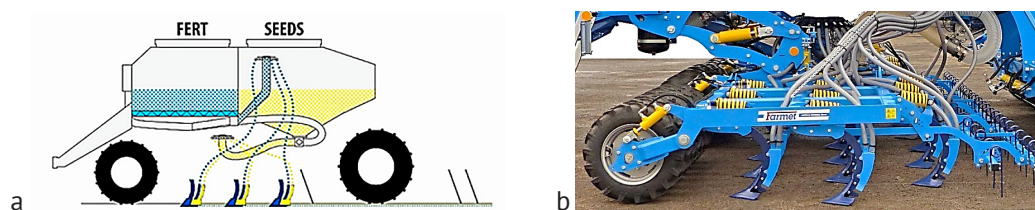


Figure 1. Falcon 6 PRO Tandem seed drill

Note: a – basic process flow diagram; b – coulter-like limbs and their arrangement

Source: compiled by the authors based on material from Farnet (n.d.a)

In seed drills, the disadvantages of tine coulters become critical when the following main conditions occur simultaneously: a wet, sticky soil surface, a large amount of poorly distributed straw residue from the previous crop, and a high operating speed. Under such conditions, crop residues accumulate in front of the shanks and in the inter-row spaces, increasing

unevenness in furrow formation, raising draft resistance and creating a risk of uneven seed covering. This conclusion was consistent with the findings of B.S. Madhusudan *et al.* (2024), who showed that the performance of working elements in conservation agriculture depended on operating speed, straw density and the ability of the coulter to cut through crop residues (Fig. 2).

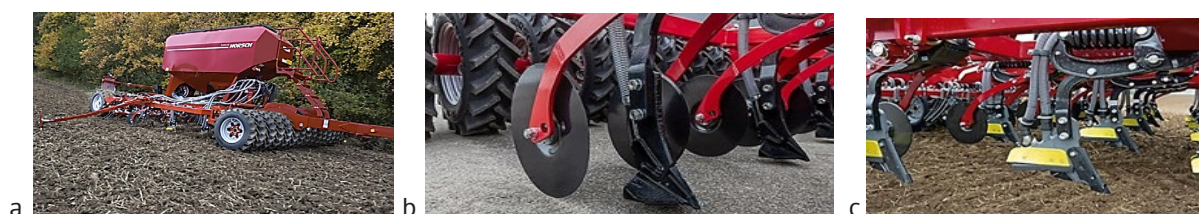


Figure 2. HORSCH Sprinter ST seed drill

Note: a – general view; b, c – coulter types and their arrangement

Source: compiled by the authors based on material from HORSCH (n.d.)

Disc and turbo-disc systems cut through crop residues more effectively and form a narrower seedbed more precisely; however, they require sufficient down-force. In a field study of different coulter types for maize, M. Benetti *et al.* (2024) found that disc coulters provided lower variability in seeding depth and seed spacing, whereas certain tine coulters designs increased plant variability. The results obtained in this study confirmed this trend: Rapid 300-400C/S, Falcon Compact, BEDNAR OMEGA, and combined units with vertical discs, such as the ALFA No-Till seed drill (Fig. 3) and Great Plains CPH + drill, demonstrated similar characteristics:

The ALFA No-Till is an integrated disc system: turbo discs pre-cut the surface layer, whilst the disc coulters form the furrow. The next unit differs from it in that the tillage attachment can be separated from the grain drill. The Green Plains 1500 (Fig. 4) received higher ratings for crop residue management and depth consistency than anchor-type monoblock machines.



Figure 4. Great Plains seed drill with CPH attachment

Source: compiled by the authors based on material from Great Plains (n.d.)



Figure 3. ALFA No-Till grain seed drill

Source: compiled by the authors based on material from ELVORTI (n.d.)

The Great Plains CPH + drill combination illustrates the modular principle, whereby the front disc section prepares the furrows for the coulters, whilst the base seed drill, in its mounted version, can be operated separately. The GREEN PLAINS 1500 utilises a similar operational layout (Fig. 5).



Figure 5. GREEN PLAINS 1500 seed drill

Source: compiled by the authors based on material from Avers-Agro (n.d.)

Modular units with a separate front section offer a wider range of adaptability. The Falcon Compact (Fig. 6) and Rapid 300-400C/S combine seedbed preparation, sowing and rolling in a single pass, and are therefore better suited to minimum tillage conditions. L. Yang *et al.* (2025) demonstrated that the stability of the sowing depth depends significantly on the operating mode of the tillage section and the quality of the seedbed levelling.

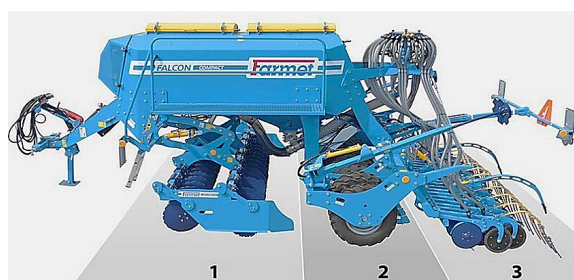


Figure 6. Falcon Compact seed drill

Note: 1 – soil-working section; 2 – pneumatic support and press wheels; 3 – attachment with disc coulters

Source: compiled by the authors based on material from Farmet (n.d.b)

Falcon Compact has clearly separated functional sections, which facilitates adjustment of the intensity of seedbed preparation. Rapid 300-400C/S provides a similar combination of operations in a more compact integrated configuration (Fig. 7).



Figure 7. Rapid 300-400C/S seed drill

Source: compiled by the authors based on material from Väderstad (n.d.)

BEDNAR OMEGA OO_FL seeding systems, like the preceding systems and those from other manufacturers, are technologically among the most flexible, as they can be equipped with different working elements, operate with fertilisers and provide several row-spacing options. However, this group requires an economic qualification: high productivity is an advantage on large areas, but for farms with limited acreage or an existing fleet of grain seed drills, the capital investment may not be economically justified. Thus, the transition from the analysis of European and American seeding systems to the DDTA for conventional grain seed drills (Fig. 8) was justified not as a technological contrast, but as a comparison of two strategies: purchasing a new universal system or modernising an existing standard seed drill for minimum tillage and direct drilling operations.



Figure 8. BEDNAR OMEGA OO_FL seed drill

Source: compiled by the authors based on material from BEDNAR (n.d.)

A relatively large number of seed drill manufacturers offer solutions for diverse operating conditions based on a strategy of purchasing a new, high-performance system with an expanded range of technological equipment. In contrast, the DDTA represents a strategy of gradual modernisation of an existing grain seed drill with a lower initial investment (Fig. 9).

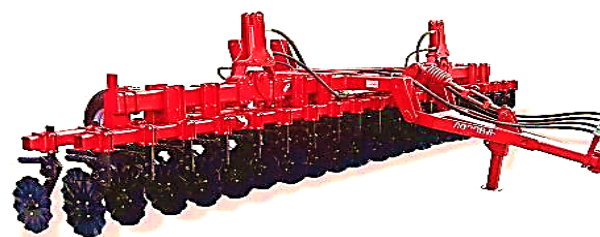


Figure 9. DDTA for a conventional seed drill

Source: compiled by the authors

To address these issues and ensure the rational use of technical resources, it is proposed to apply a multi-objective optimisation model for the selection of seed drills. It has been developed with the aim of

enabling a scientifically sound selection of sowing machinery for farms operating under traditional, minimum tillage and direct-seeding (“no-till”) systems. The model takes into account a range of economic, agronomic and environmental criteria, which are often conflicting in nature. Thus, the problem is formulated as a multi-objective optimisation problem involving the construction of a Pareto front. The use of the model helps to reduce subjectivity in decision-making, improve the efficiency of the machinery and tractor fleet, and achieve a balance between economic, agronomic and environmental criteria. As there were no comparable field data or operating costs available for all nine alternatives, a simplified integrated preliminary selection indicator, described below, was applied for the computational validation.

For each seeding unit, an assessment matrix was developed using six criteria: *T* – technological versatility; *R* – crop-residue handling capability; *D* – depth stability; *M* – manoeuvrability; *E* – energy and economic accessibility; *U* – modularity and maintainability. Criterion *T* accounted for suitability for conventional, minimum-tillage and direct drilling; *R* – the type of working elements, ability to cut through crop residues and residue clearance between the rows; *D* – the ability to follow field microrelief, adjustment of downforce and coulter stabilisation; *M* – working and transport width and the complexity of turning manoeuvres; *E* – power requirements, the possibility of using an existing tractor and relative capital affordability; *U* – the possibility of using modules separately, row-spacing adjustment and maintenance using standard equipment (Table 2).

Table 2. Theoretical validation of the integrated adaptability index

Unit	<i>T</i>	<i>R</i>	<i>D</i>	<i>M</i>	<i>E</i>	<i>U</i>	A_i	Rank
DDTA + standard grain seed drill	0.90	0.80	0.70	0.55	0.90	0.95	0.800	1
Rapid 300-400C/S	0.85	0.75	0.85	0.75	0.70	0.75	0.783	2
Great Plains CPH + drill	0.90	0.80	0.75	0.60	0.65	0.90	0.773	3-4
BEDNAR OMEGA OO_FL	0.95	0.85	0.85	0.60	0.45	0.85	0.773	3-4
GREEN PLAINS 1500	0.80	0.75	0.70	0.65	0.75	0.75	0.735	5
Falcon Compact	0.80	0.75	0.75	0.70	0.65	0.70	0.730	6
ALFA 4/6 No-Till	0.70	0.70	0.60	0.70	0.85	0.55	0.680	7
HORSCH Sprinter ST	0.75	0.60	0.60	0.75	0.70	0.60	0.668	8
Falcon 6 PRO Tandem	0.70	0.65	0.65	0.80	0.55	0.60	0.660	9

Note: *T* – technological versatility; *R* – residue handling; *D* – depth stability; *M* – manoeuvrability; *E* – energy and economic accessibility; *U* – modularity and maintainability; A_i – integrated adaptability score of the *i*-th seeding unit in soil preparation technologies

Source: compiled by the authors based on the research results

The mean value of the integrated indicator was 0.733, the standard deviation was 0.053, and the coefficient of variation was 7.23%. This indicates that the differences between the modern seeding units were not radical, but were sufficient to form a group of more adaptable solutions. An automated analysis in Python 3.13 using 1,000 scenarios with variations in the weighting coefficients within $\pm 10\%$ showed that the combination of the DDTA with a standard seed drill retained first place in 100% of the scenarios; the mean Spearman rank correlation coefficient between the baseline and modified rankings was 0.99. Thus, the conclusion regarding the feasibility of the modernisation option was robust within the adopted system of criteria. The advantage of the DDTA was explained not by absolute technological superiority, but by the balance of the criteria. The attachment has an adjustable working width of 3.6, 5.4 and 6.0 m, vertically arranged corrugated discs with a basic row spacing of 15 cm, and a design that allows the spacing between the working elements to be adjusted. Combined with a standard grain seed

drill, it performs strip preparation ahead of the coulters, reduces the need for separate seedbed preparation and retains the possibility of using the base seed drill under conventional cultivation. This dual functionality resulted in a high score for criteria *E* and *U*. At the same time, the score obtained does not demonstrate the superiority of the DDTA over standard seeding systems in terms of reliability, durability or service life, as these characteristics require separate experimental validation.

Comparison with other studies supported the results obtained. L. Liu *et al.* (2024) developed a depth-control strategy based on measuring the downforce of a T-shaped coulter and showed that seeding depth depends on the interaction between downforce, soil moisture and soil bulk density. Although the present study did not include active coulter control, this research confirmed the need to consider depth stability as one of the principal criteria for machinery selection. L. Liu *et al.* (2023), using discrete element modelling, demonstrated the effect of a T-shaped coulter on straw and soil; this was consistent with the present

conclusion that a simple comparison of working width without analysing interaction with crop residues does not provide an objective assessment of adaptability. Researchers Y. Gao *et al.* (2025) investigated the seeding quality of a ridge-clearing no-till seed drill under strip-till conditions and demonstrated that strip preparation parameters influenced the uniformity of the seedbed. The results followed a similar logic: machines that formed a strip or cut through crop residues in front of the coulter received higher *R* and *D* ratings. K.K. Lakshena *et al.* (2025), in a long-term study of conservation tillage, emphasised that the system's productivity depended on the compatibility of sowing technology, fertiliser application and soil condition. This supported the inclusion in the model not only of agronomic criteria, but also of environmental and economic criteria.

L. Oliveira *et al.* (2025) showed that different downforce settings affected soil compaction, seeding depth and crop development. In the present study, this was accounted for through criterion *D* and through limitations associated with monoblock frames: where working elements lack individual surface-following capability, field microrelief becomes a critical factor. B.L. Beres *et al.* (2025) established that coulter type in direct drilling affects seed placement and plant development; this confirmed the need to distinguish between disc, tine and combined systems rather than treating them as a single group of No-till seed drills. Thus, the conclusions of this study emphasise that increasing the productivity of a seeding unit should be subordinate to maintaining depth stability and uniformity, rather than the reverse. For tine coulters, critical conditions included wet, heavy soils, long uncut straw, inter-row spaces with limited residue clearance and operating speeds at which the working elements could not self-clean effectively. For disc systems, critical conditions included excessively dry or highly compacted soils, where the disc could not maintain a stable depth without sufficient downforce. For large seeding systems, a critical factor was a mismatch between their productivity and the farm's cultivated area, which increased unit capital costs. For the DDTA modernisation solution, the critical factor remained the proper matching of attachment width, row spacing, the mass of the standard seed drill and appropriate tractor power. Thus, the proposed attachment was not considered a universal replacement for all modern seeding systems. Instead, it was identified as a rational alternative for farms that already have serviceable grain seed drills and seek to transition to minimum-tillage or direct drilling without simultaneously purchasing an expensive seeding system.

A limitation of the study was that the assessment of adaptability was analytical and calculation-based,

relying on publicly available technical data and standardised expert criteria. At the same time, this methodology is suitable for the preliminary selection of machinery when a farm is comparing several design alternatives before conducting field trials. A further limitation is the lack of standardised data in publicly available sources on reliability, durability, mean time to failure and overall service life. Thus, the ranking results should be used only for the preliminary selection of alternatives, followed by field and economic validation.

CONCLUSIONS

The study carried out a design and technological analysis of modern seed drills for conventional, minimum and direct sowing and established that the adaptability of a sowing unit is determined not only by the type of coulter, but also by the combination of layout, method of seedbed preparation, micro-relief tracking, the handling of crop residues, energy availability and the possibility of using modules separately. Monoblock anchor seed drills offer advantages in terms of compactness and manoeuvrability, but their shortcomings become apparent on wet, heavy soils with large amounts of straw and at high travelling speeds. Disc and turbo-disc systems handle crop residues better and form a more stable seedbed, but require sufficient downforce and more precise adjustment.

Simulation testing of the multi-purpose model showed that the highest overall adaptability index was achieved by combining the DDTA with a standard grain seed drill ($A_i = 0.8$). This is not due to superiority across all agronomic parameters, but rather to a balanced combination of technological versatility, adjustable row spacing, affordability, maintainability and the potential to modernise the existing fleet of machinery and tractors. The group of rational alternatives also included the Rapid 300-400C/S, Great Plains CPH+ drill and BEDNAR OMEGA OO_FL, confirming the suitability of modular and combined configurations for farms employing different cultivation technologies. The ranking presented does not prove the absolute technical superiority of the DDTA over mass-produced complexes, as the criteria of reliability, durability and service life were not assessed due to the lack of comparable experimental data.

The study substantiated the logical transition from the analysis of complex European and American seeding systems to the Ukrainian modernisation solution represented by the DDTA. At present, complex systems offer advantages in terms of productivity, equipment configuration and precision; however, they require significant capital expenditure and a more powerful tractor. The DDTA is a rational option for farms seeking to improve the suitability of a standard grain seed drill

for minimum-tillage or direct-drilling systems without completely replacing the existing machinery. The practical significance of the results lies in the possibility of using the proposed system of criteria for the preliminary selection of seeding machinery by agricultural engineering departments, in education and in consultancy. Further research should focus on field testing of the DDTA in combination with different standard seed drills, determining actual draft requirements, fuel consumption, depth stability, emergence uniformity and its effect on soil compaction. It is also advisable to

investigate the economic payback of the modernisation for farms of different sizes.

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Адаптивність сівалок у сучасних технологіях вирощування сільськогосподарських культур

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Анотація. Актуальність дослідження зумовлена тим, що перехід господарств від традиційного обробітку ґрунту до мінімальних і No-till технологій потребує сівалок, здатних стабільно працювати за різної кількості пожнивних решток, вологості та мікрорельєфу поля. Недостатня узгодженість між конструкцією посівного агрегату і технологією вирощування призводить до нерівномірного загортання насіння, перевитрат палива та зростання вартості оновлення машинно-тракторного парку. Метою дослідження було обґрунтування адаптивності сучасних моноблокових, модульних і комбінованих сівалок та оцінка доцільності використання ґрунтообробної приставки прямої сівби (ППС) із серійними зерновими сівалками. Методологія дослідження передбачала порівняльний конструктивно-технологічний аналіз посівних агрегатів за уніфікованими критеріями, нормування показників у шкалі 0-1, багатоцільове ранжування та перевірку стійкості результатів за зміни вагових коефіцієнтів. Проаналізовано робочі органи, ширину захвату, міжряддя, тягову потребу, можливість роботи у традиційній, мінімальній і прямій сівбі, а також умови, за яких недоліки окремих конструкцій ставали критичними. Статистичний аналіз включав визначення середнього значення, вибіркового стандартного відхилення, коефіцієнта варіації та рангової кореляції Спірмена. Отриманий результат характеризує попередню порівняльну придатність за прийнятою системою критеріїв і не є доказом абсолютної технічної переваги ППС без польової перевірки надійності, довговічності, робочого ресурсу. Встановлено, що найвищу універсальність забезпечували агрегати з відокремленою ґрунтообробною секцією та посівним модулем, оскільки вони поєднували підготовку посівної смуги з можливістю використання сівалки окремо. Розрахункова апробація показала, що варіант ППС із серійною сівалкою увійшов до групи Парето-раціональних рішень завдяки кращій економічній доступності, регульованому міжряддю та придатності до модернізації наявної техніки. Водночас складні європейські посівні комплекси мали перевагу за стабільністю глибини та технологічним оснащенням, але потребували більшої потужності трактора і вищих капітальних витрат

Ключові слова: No-till; мінімальний обробіток ґрунту; сошник; посівний агрегат; пожнивні рештки; ресурсозбереження; багатокритеріальна оптимізація