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Smart Strip-Till One-Pass Machine: Winter Wheat Sowing Accuracy Assessment

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Abstract: Modern agricultural machines are subject to requirements that result from developments in plant cultivation technology and environmental care. Agricultural practice demands multifunctional machines that perform several agrotechnical treatments in a single pass. Automated and digitalised management of machines and their working parts is also becoming standard. A strip-till one-pass machine was designed that automatically regulates and monitors sowing rate and depths and the application of fertiliser to loosened soil strips. Among other things, an electro-hydraulic depth regulator with a built-in linear potentiometer and an overload sensor was used. Laboratory and field tests assessed the accuracy of the rate and depth of sowing wheat grain and fertiliser application by the innovative machine. This study confirmed the machine's high quality of wheat sowing. The accuracy of the operating parameters was not less than 97% in laboratory tests and 92% in field conditions. The field emergence capacity of wheat was 88% and its sowing density can be considered good. The machine provides uniform operation of all 11 multifunctional assemblies (units, sections of loosening-applying tines and sowing coulters). The coefficient of variation (CV) of grain sowing and granular fertiliser application by individual assemblies was in the range of 4.27–7.29% and 3.74–6.90%, respectively. The sowing depth accuracy expressed as an accuracy coefficient (DA) was 87.33–93.67% with CV 4.62–9.65%. The machine's introduction onto the market can facilitate field cultivation of plants in accordance with the principles of conservation agriculture and Agriculture 4.0.

Keywords: agricultural machinery; depth regulator; strip tillage; fertiliser; sowing grain; sowing depth; emergence capacity

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1. Introduction

Agriculture 3.0 and 4.0 integrate automation, robotisation and elements of IT to optimise agricultural production processes. It manifests in the implementation of modern machines and plant cultivation technologies that increase productivity, reduce human labour input, reduce costs and limit adverse environmental impacts [1,2]. Today, agriculture is evolving to meet the needs of contemporary society, where the food supply is secured through practices such as water and soil conservation and a reduction in agrochemicals, ensuring the production of high-quality crops. A necessary prerequisite for ensuring all of the above is the use of well-functioning agricultural machinery [3]. Digital technologies, automation and autonomisation are being adapted to agricultural machines and tools, including those for soil tillage, fertilisation and sowing. They enable the use of variable seed and fertiliser doses, automatic control of the operations of machine parts responsible for key cultivation processes, and performance monitoring [4,5]. Progress in techniques and technologies is being made in all aspects of modern field crop cultivation, including soil tillage, fertilisation and sowing, which are increasingly being combined into a single process [6]. One trend in contemporary agricultural mechanisation is the construction of multifunctional machines. One machine can perform many agrotechnical operations, from soil tillage to seed harvesting [7].

The development of soil cultivation technologies and techniques includes innovative solutions relating to both the methods and machines of cultivation, covering construction, functionality, operating parameters and their monitoring, and decision-support systems [8,9]. Among the new reduced-till methods, strip-till occupies an important and growing position [10,11]. However, such tillage, especially when combined with the simultaneous application of fertilisers and sowing of seeds (i.e., strip-till one-pass) requires specialised machinery [12].

Agricultural mechanisation also includes seed drills and machines for simultaneous sowing and fertilising. Design work is mainly focused on creating innovative, multifunctional machines that can perform agrotechnical tasks in a variety of agricultural systems and socio-economic conditions [13–15]. Particular attention is paid to solutions that determine the precision, uniformity and accuracy of seed sowing or fertiliser application. Therefore, research is focused on various of the assemblies and working parts of these machines, such as tanks, distributors, seed-transfer systems, and multifunctional assemblies for soil tillage and sowing seeds [16,17].

In the era of development of smart agriculture, automation, digitalisation and real-time environmental conditions monitoring systems are increasingly present in agricultural machines. These technologies support or replace mechanical operations in the field of precise traction of machines, their control and regulation of operating parameters during soil tillage, sowing, fertilisation, plant protection, harvesting [18]. Smart monitoring systems based on the Internet of Things technology analyse soil and field conditions, such as: moisture, temperature, pressure, light, air composition, CO_2 content, pH, NPK. This technology also has the ability to collect and transmit large amounts of data used in real-time and for planning agricultural operations [19]. Newly designed, innovative agricultural machines and tools are equipped with an increasing number of sensors for real-time operation monitoring and systems for automatic adjustment of working elements, e.g., stereo vision cameras, LiDAR, radars, thermal cameras, RGB cameras and laser scanners [20]. A sensor system comprising a linear potentiometer, inclinometer and optical distance sensor can measure the depth to which working parts penetrate the soil [21]. Sensors and automation systems are also used in shallow surface-cultivation tools. Rotary harrows equipped with stereo cameras that assess the levelling of the soil surface, and the size of soil aggregates make it possible to control the intensity and accuracy of seedbed cultivation required for precise seed sowing [22].

Ultrasonic sensors and linear differential sensors are used to precisely assess seeding depth in field conditions. Infrared sensors or photoelectric sensors are suitable for controlling seed rate and flow in seed transport ducts. It is essential to monitor these seeder parameters to ensure high-quality sowing and, consequently, uniform plant emergence [23]. Systems for monitoring sowing depth are also being developed, especially in high-speed seed drills. This is performed using combined data from laser, ultrasonic and angle sensors [24]. Environmental-condition sensors and work-monitoring systems based on the

Internet of Things are also used in reduced-tillage machines, e.g., no-till seed drills [25]. In modern seed drills, operating parameters such as depth, quantity and distribution of seeds in the soil are monitored and corrected in real time [26]. Sensors, as well as advanced control, data collection and processing systems enable the construction of next-generation machines. These include drones, robots, and autonomous machine [27,28].

In recent decades, there have been rapid advances in strip-till machines and their working parts [29,30], including in one-pass strip-till technology, which involves the tilling of soil strips, application of fertilisers and sowing of seeds to be performed simultaneously [31]. New and improved machine designs can operate even in difficult soil conditions [32]. Wang et al. [33] presented a strip-till machine with a system to automate the regulation of cultivation depth and the width of soil strips cleared of plant residues. Particular attention is being paid to constructing hybrid multifunctional strip-till machines enabling the sowing of various plant species while maintaining high-precision seed sowing [34].

An important sowing parameter that determines emergence and plant population is its accuracy. The distribution of seeds in the soil is also important for the growth of plants [35]. Seed-sowing precision depends on, among other things, seedbed preparation, sowing depth, seeder speed, and the number of seeds in the hopper [36,37]. No less important are the design solutions for the parts that convey seeds and determine dose sizes in seed drills [38]. The horizontal and vertical distribution of seeds in the soil depends on the adopted inter-row spacing and in-row plant spacing, sowing depth, pre-sowing soil preparation, technical parameters of the seeder, and operator skills. The indicators of sowing quality include the arithmetic mean of the seed spacing, the standard deviation of the plant spacing, and the coefficient of variation [39]. The density and uniformity of plants in the field resulting from different sowing techniques and methods are assessed by counting in the field or by image analysis [40]. The assessment results are expressed as indices created using statistical analysis and mathematical modelling [41,42], often using the coefficient of variation [43].

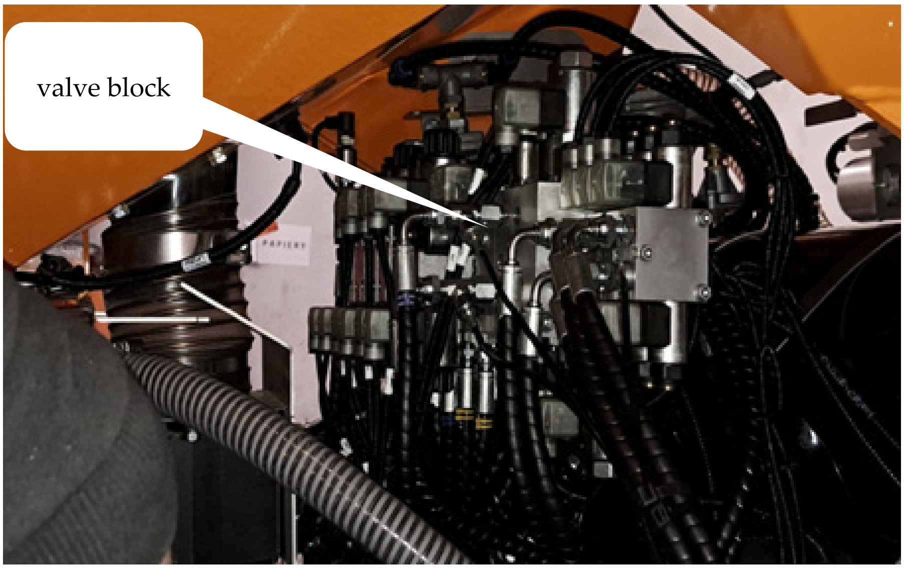
In line with the global trend of agricultural technological development, a consortium consisting of an agricultural machinery manufacturer, a research and development facility, and Poznań and Bydgoszcz universities of technology undertook to develop an automatically managed, regulated and monitored strip-till one-pass machine. The research hypothesis was that the introduced design and functional changes will allow the creation of a strip-till one-pass machine with automated regulation of basic operating parameters of working elements and the possibility of their real-time adjustment to changing conditions of crop fields. It will therefore be possible to abandon manual settings and rely on the subjective assessment of the operator during these activities. During industrial research and development work, the accuracy of the rate and depth of wheat grain sowing and the amount of granular fertiliser applied were tested, assuming that the field emergence capacity would be above 80% to ensure good plant density after emergence.

2. Materials and Methods

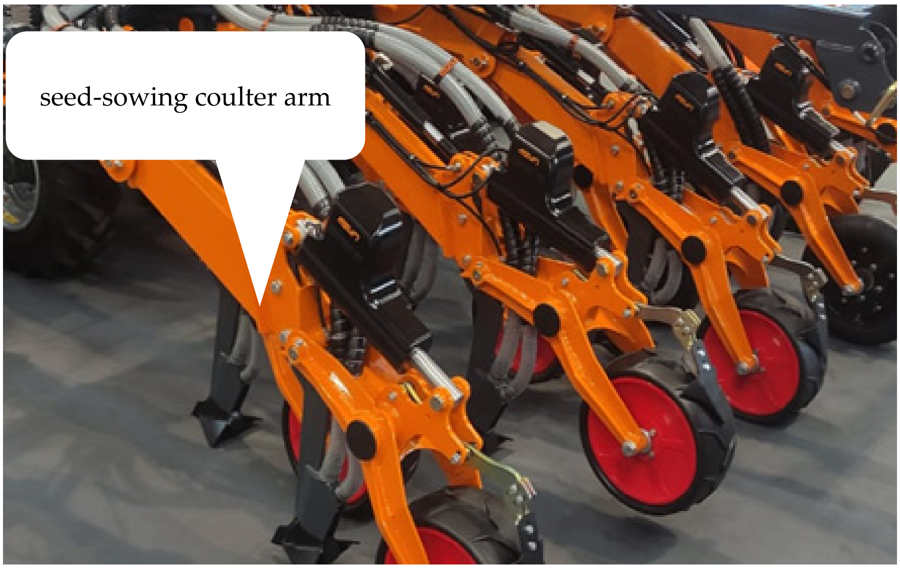
2.1. Subject, Scope and Location of Research

The subject of the research was a new model of Mzuri hybrid machine adapted to the strip-till one-pass technique used in the field cultivation of various crop species. The machine is equipped with sensors monitoring soil properties necessary for automatic control of operating parameters, i.e., depth of soil strip loosening, seed sowing depth and pressure force of the ground-following soil-consolidating wheel. The research and development work also results in new mechanical and electro-hydraulic solutions enabling automatic change in machine operating parameters in real time. The design and construction challenge was not only to determine the accuracy and range of operation of sensors and control elements, but also their mechanical implementation with the machine. Due to the difficult working environment—soil, stones, moisture, dust, and plant residues—the first prototypes of soil property assessment sensors were damaged and/or their operation was disrupted. Ultimately, the soil property sensors were mounted directly behind one of the loosening tines. The measurement of soil volumetric moisture and variation in relative soil compaction measured in real time or read from the field map are the basic elements of the algorithms for automatic management of the working depth of the loosening tines and sowing coulters, as well as the pressure force of the soil-consolidating wheels. Currently, seeds and fertiliser are evenly distributed from the central split tank to the working assemblies by two independent pneumatic heads. A central block of electro-magnetic and hydraulic valves (Figure 1A) manages the automatic regulation and monitoring systems of the operation of 11 multifunctional assemblies—sections of loosening-applying tines and sowing coulters. Each of these assemblies features four key elements. The first is a disc that cuts through the surface and clears residue, which is an existing solution, and so was not the subject of analysis herein. The second is a novel integrated soil-loosening tine with fertiliser-placement applicator. The final ground-contacting element is an innovative seed-sowing coulter (Figure 1B) combined with the ground-following soil-consolidating wheel. In earlier models of the machine, this connection was made by screws. The operator manually adjusted their length, and thus the sowing depth and wheel pressure force. These parameters were selected intuitively and were not changed during work in the field, despite differences in soil properties in different parts of the field. In the innovative solution, the screws were replaced with a cylinder and an electro-hydraulic regulator (Figure 1C). Its extension and wheel contact force depend on the soil conditions (structure, moisture) included in the device control algorithms. In dry, light soil, the coulter is sunk and the wheel pressure force increases so that the seeds have more favourable water conditions for germination. In heavy, moist soil, the coulter works shallowly and the wheel has less pressure force, reducing the risk of soil crusting after sowing. The sowing depth regulator installed in the machine was developed as a result of many critical studies of previous commercial electric and electro-hydraulic solutions. These devices (Figure 2A,B) were not sufficiently resistant to unfavourable weather conditions, did not have an appropriate response and controllability in real time, as well as durability in previously uncultivated soil and with a large amount of crop residue on the field surface. Only a controller with a built-in encoder and overload sensor (Figure 2C) could be used in the machine, meeting the design and functional assumptions in field conditions. The controller has a built-in linear potentiometer enabling automatic control and monitoring of the working depth. A solution similar in principle of operation also enables automatic regulation of the working depth of the loosening tines and its ongoing monitoring. For this purpose, a hydraulic cylinder with a built-in potentiometer was developed (Figure 3). The diagram of the hydraulic system of the valve block responsible for the smooth regulation of the working depth of the tine section and seed-sowing coulters is shown in Figure 4. For example, the algorithm of the tine working depth taking into account the soil properties determines the position of the potentiometer by opening the valve (4/3 flow direction control valve with control—Figure 4A). In turn, the pressure force of the compacting wheel behind the seed-sowing coulter depends on the oil pressure supplied to the cylinder, which is regulated by a valve placed in the system (System pressure regulating valve—Figure 4B). The quantities of dosed material (seeds, fertiliser) are monitored in real time by flow optical sensors (Figure 5). All sensors, control and regulation systems are managed by a central computer.

(**A**)

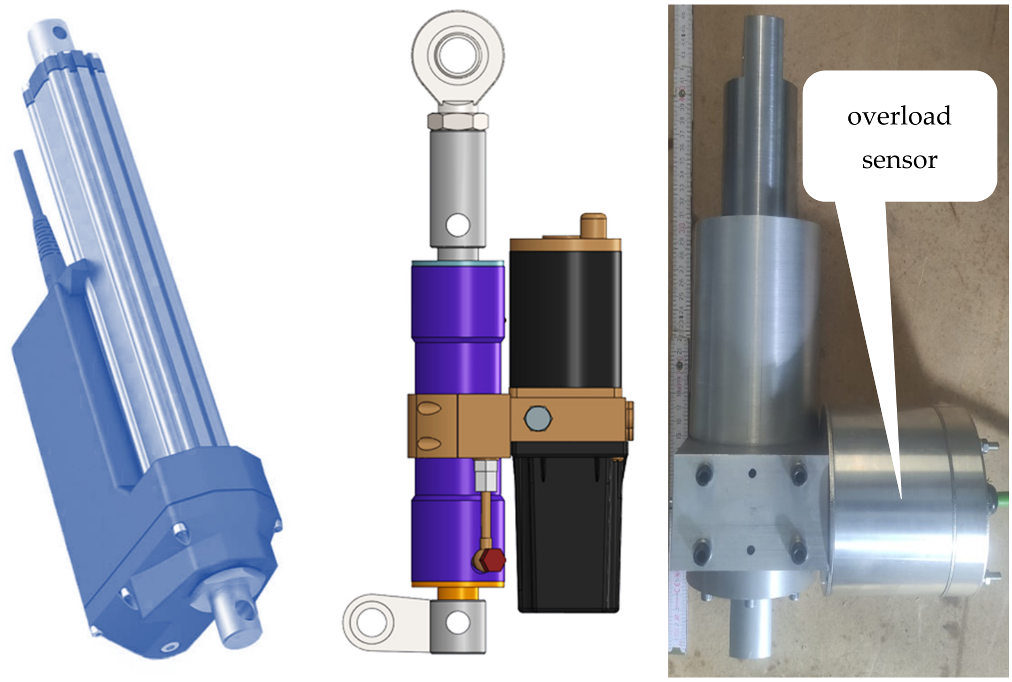


(**B**)



(**C**)

Figure 1. Central block of electro-magnetic and hydraulic valves (**A**), seed-sowing coulters (**B**), and electro-hydraulic regulator of soil-working depth (**C**) of strip-till one-pass machine.



(**A**) (**B**) (**C**)

Figure 2. Coulter and tine depth regulators; electric (**A**), electro-hydraulic (**B**), with a built-in encoder and overload sensor (**C**).

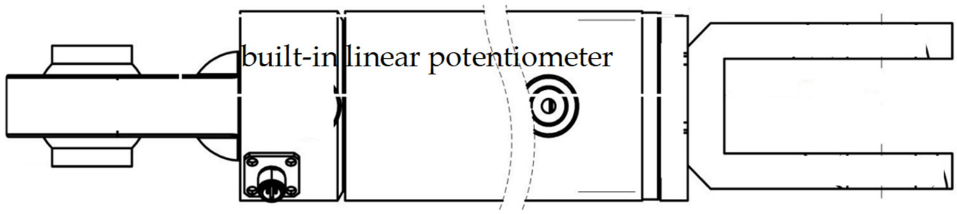


Figure 3. Working depth control cylinder with built-in linear potentiometer.

The design works and machine operation tests were performed at Mzuri World Sp. z o.o. and the Research and Development Center Agro-Means-Technique-Technology in Śmielin (53°09′04.0″ N; 17°29′10.7″ E), Kuyavian-Pomeranian Voivodeship, Poland with the participation of employees of the Departments of Agronomy of the Bydgoszcz University of Technology and Poznań University of Technology, Poland. The work was carried out in 2021–23 as part of the AGROTECH project co-financed by the European Union.

2.2. Laboratory Tests and Field Studies

In the first stage of industrial research, laboratory tests were carried out to determine the accuracy of the sowing amount of winter wheat grain and granulated fertiliser by, respectively, each coulter and each loosening-applying tine—ten repetitions. The research used wheat seed with a thousand-grain weight of 44 g and a utility value of 88%, assuming a sowing rate of 150 kg/ha. The fertiliser used for the tests was Polidap [NP (S), 18–46 (5)]. Ninety-two percent of the product is in the form of granules with dimensions 2.0–5.0 mm and bulk density 0.85–0.95 kg/dm^3. The fertiliser was applied at a dose of 150 kg/ha.

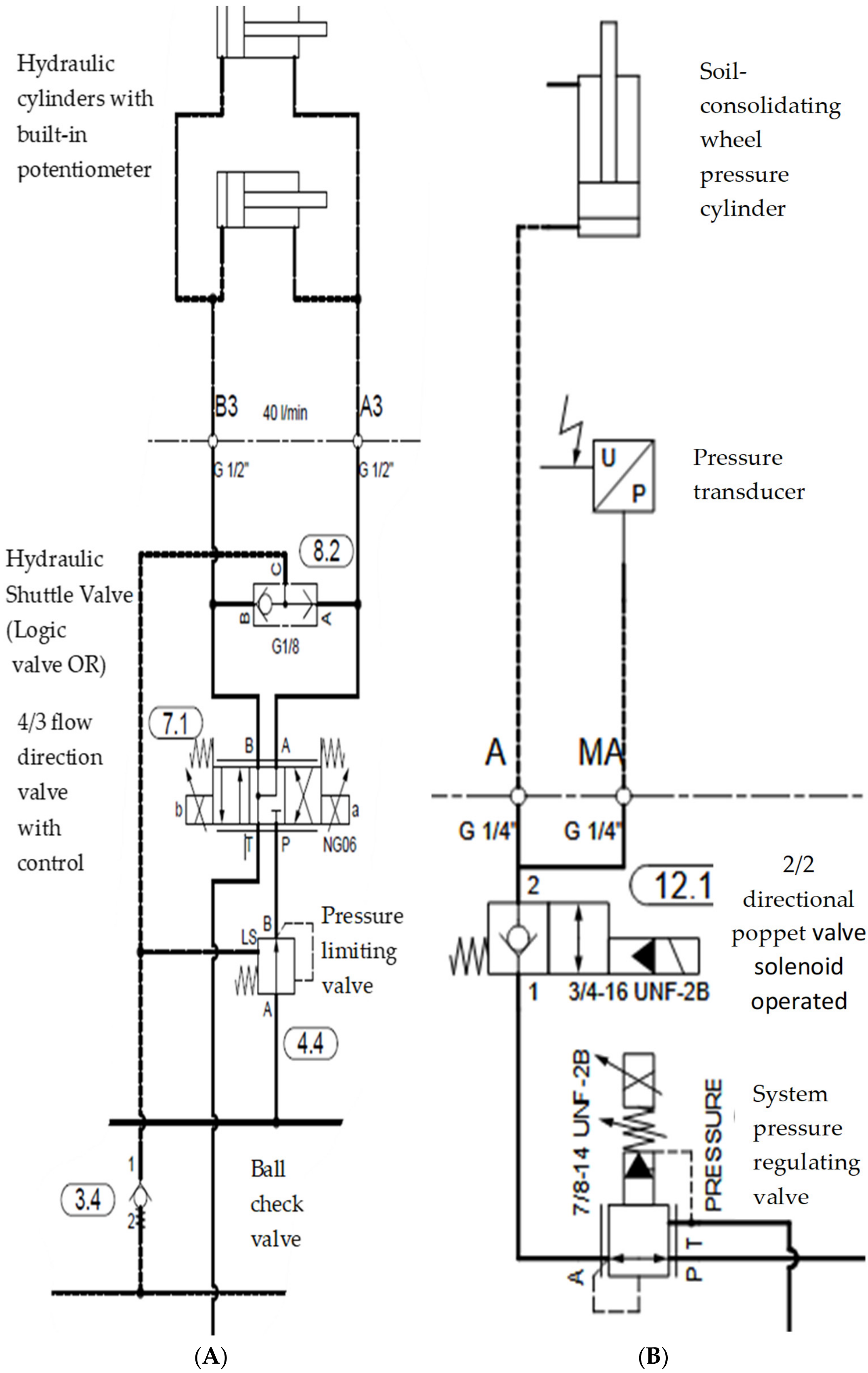


Figure 4. The diagram of the hydraulic system of the valve block responsible for the regulation of the working depth of the tine section (**A**) and seed-sowing coulters (**B**).

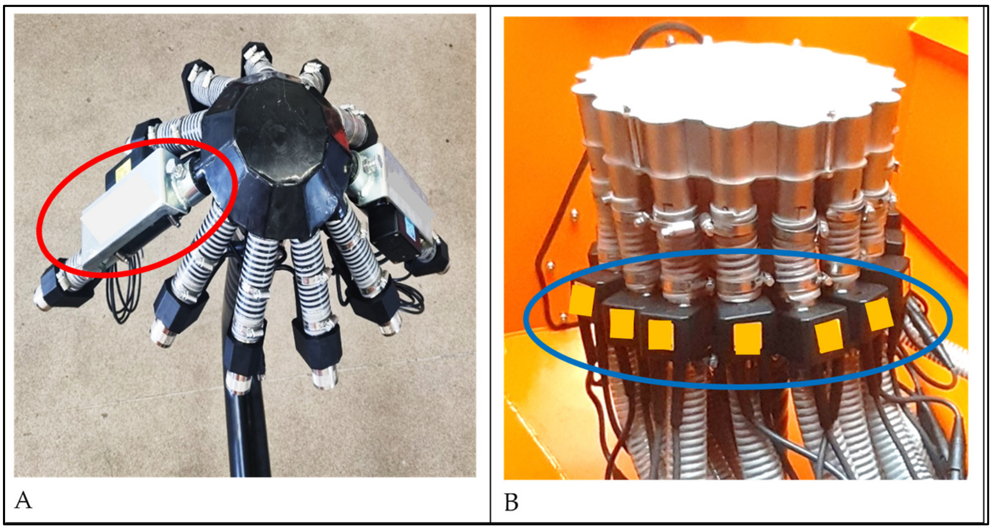


Figure 5. Flow optical sensors: seed head (**A**) and fertiliser head (**B**).

The indicators used as a measure of the accuracy of grain sowing and fertiliser application were those consistent with the sowing accuracy (SA) formula presented in the work of Liu et al. [44]. The accuracy of grain sowing and fertiliser application by individual coulters and loosening-applying tines was assessed on the basis of a test operation of the machine corresponding to work on an area of 0.1 ha. The test was repeated ten times. The data collected on the amount of grain and fertiliser from each of the 11 assemblies were converted into the values of the accuracy of grain sowing index (GA) and fertiliser application index (FA) according to the formulas:

$$GA = (1 - |(WGm/WGt) - 1|) \times 100\% \quad (1)$$

where WGm—grain mass measured during the test; WGt—theoretical grain mass resulting from the assumed sowing quantity (13.64 kg/coulter), and:

$$FA = (1 - |(WFm/WFt) - 1|) \times 100\% \quad (2)$$

where WFm—fertiliser mass measured during the test; WFt—theoretical fertiliser mass resulting from the assumed dose (13.64 kg/placement tine).

In the second stage, field tests were performed on Cambisol (loamy sand), with a soil volumetric moisture content of 11–17% after harvesting winter rape with crop residues on the field surface. The research site is located in the zone of influence of humid continental climate (cold, without dry season, warm summer). The average annual air temperature is 8.1 °C, and the total rainfall is 485 mm. The machine's travel speed was 8 km/h. Similarly to the first stage, the accuracy of seeding and fertiliser placement was tested. In addition, the accuracy of the working depth of the seeding coulters in the soil was assessed. The sowing depth accuracy index (DA) was calculated based on ten measurements of seed placement depth for each coulter relative to the assumed optimal depth of 3 cm, as follows:

$$DA = (1 - |(Dm/Dt) - 1|) \times 100\% \quad (3)$$

where Dm—depth of seed placement during the test; Dt—assumed optimal sowing depth.

In a field experiment, after sowing winter wheat on 2.5 ha at a density of 250 grains/m^2 and a field emergence capacity of 87%, the uniformity of plant density was assessed in a strip corresponding to the working width of the machine. The uniformity of planting in each of the 11 rows spaced 36.4 cm apart was determined by calculating the accuracy of the number of plants (PA) based on the number of plants per metre and the optimal number of plants according to the assumed seed material and sowing parameters.

$$PA = (1 - |(Pm/Pt) - 1|) \times 100\% \quad (4)$$

where Pm—number of plants detected after emergence; Pt—optimal number of plants according to the assumed sowing parameters—79.1 plants per 1 m of row.

2.3. Analysis of Results

The results of laboratory and field tests were statistically processed. The actual measurement data of individual sowing and plant emergence parameters and fertiliser placement are given in tables. Basic statistics (average, minimum, maximum, standard deviation, coefficient of variation, standard error) are presented for each coulter assembly and on average for the working width of the machine. The measurement data and theoretical data (those assumed as the standard) were used to calculate average accuracy indices values for each assembly, as well as error values and standard deviations. These values for each index are presented as box-and-whisker graphs illustrating each of the 11 assemblies. Based on all the measurement data determining the value of the accuracy index of a specific sowing parameter (from all assemblies and repetitions, n = 110), its coefficient of variation (CV) was calculated.

$$CV = (\text{standard deviation}/\text{mean value of measurements}) \times 100\% \quad (5)$$

Statistical analysis was performed using the Statistica.PL 12 program [45].

3. Results

In a static laboratory test, assuming the placement of 13.64 kg of wheat grain and 13.64 kg of fertiliser by each assembly, it was found that an average 0.18 kg more grain was sown than assumed and 0.09 kg less fertiliser was applied. The weight of grain sown by the machine ranged between 13.30 kg and 14.06 kg, while the weight of fertiliser was between 13.38 and 13.73 kg. In the field test, the corresponding difference between optimal and actual placed amounts of grain and fertiliser was 0.03 kg and 0.41 kg, respectively. The difference between the maximum and minimum size is 1.27 kg of grain and 1.06 kg of fertiliser. The standard deviation, coefficient of variation and standard error of the amount of grain sown and fertiliser applied in the field tests were higher than in the laboratory tests (Table 1). The sowing depth and the number of plants after emergence obtained by the Mzuri machine in field tests did not differ significantly from the assumed optimal values. These differences were 0.24 cm and 1.3 plants/m of row, respectively. The CV of none of the sowing parameters in the laboratory and field tests exceeded 3.50%.

There was a greater variation in sowing parameters among the 11 assemblies than in the average work of the entire machine (Table 2). The CV of seed sowing rate and fertiliser application in the laboratory was 2.19–3.46% and 2.49–5.36%, respectively, while in field conditions it was 4.27–7.29% and 3.74–6.90%. An even higher CV (7.98–11.71) was found for the variability of sowing depth. The variability in sowing depth was greatest in the outer coulter assemblies and smallest in those in the middle of the machine. The average CV for the working depth of the four central assemblies is 8.59%, and that of the four outermost, (two left and two right outermost) was 10.00%. The variability (CV) of number of plants after emergence in a 1-m section of row ranged from 5.63% to 10.43%.

Table 1. Laboratory and field tests of the strip-till machine operation—average results of all sowing coulters and loosening-applying tines.

Parameter	Unit	Average	Minimum	Maximum	Standard Deviation	Coefficient of Variation (%)	Standard Error
Laboratory tests							
Sowing grain	kg	13.82	13.30	14.06	0.31	2.24	0.10
Fertiliser application	kg	13.55	13.38	13.73	0.11	0.84	0.04
Field tests							
Sowing grain	kg	13.61	12.98	14.25	0.48	3.49	0.15
Fertiliser application	kg	14.05	13.52	14.58	0.35	2.52	0.11
Sowing depth	cm	2.76	2.64	2.89	0.07	2.58	0.02
Number of plants	pcs./m	80.38	78.36	83.18	1.50	1.87	0.48

Table 2. Coefficient of variation (CV (%)) of the working parameters of the individual machine assemblies.

Parameter	Assembly										
	1	2	3	4	5	6	7	8	9	10	11
Laboratory tests											
Sowing grain	2.19	2.40	2.59	3.06	2.43	2.57	2.25	3.22	2.61	3.46	2.59
Fertiliser application	2.49	4.67	4.26	5.05	4.83	5.36	3.11	3.04	3.91	4.98	3.49
Field tests											
Sowing grain	5.00	5.98	7.27	5.77	4.27	6.59	6.31	5.88	6.06	7.29	6.09
Fertiliser application	5.45	6.71	5.06	6.43	3.74	6.90	3.92	3.92	4.77	4.87	4.92
Sowing depth	9.76	9.51	10.07	8.55	9.51	7.98	8.32	11.71	11.20	10.06	10.66
Number of plants	8.45	5.63	8.74	7.24	10.43	9.79	8.23	6.76	6.00	8.50	8.33

In laboratory tests, the wheat grain sowing accuracy of individual assemblies was generally greater in the central part of the machine and lower at the sides. The GA index value ranged from 96.47% to 97.87% (Figure 6). Fertiliser application accuracy did not depend on loosening-applying tine position relative to the machine's centre line. The highest FA index (97.57%) described the work of assembly 7, and the lowest (95.37%) was for assemblies 4 and 6 (Figure 7).

In field tests, the accuracy of grain sowing (GA) and fertiliser application (FA) by individual assemblies did not depend to a large extent on their position on the machine. The grain was sown most accurately by coulter 5 and the least accurately by coulter 10. The maximum difference in GA index was 3.67 percentage points (Figure 8). The analogous difference in the FA index value was 2.72 percentage points and was the result of the most and least accurate applications (respectively, loosening-applying tines 3 and 4) (Figure 9).

The accuracy of working depth of the four central coulters was greater than that of the outer ones. The average DA index was 92.75% for the four central coulters, 88.67% for the three left outermost, and 88.42% for the four right outermost. The least stable in the soil was coulter 8 (DA = 87.33%), while the most stable was coulter 4 (DA = 93.67%) (Figure 10).

The uniformity of winter wheat density in the 11 individual rows, as expressed by the precision index of the number of plants (PA) per 1 m of row ranged from 91.00% for row 5 to 93.86% for row 2 (Figure 11).

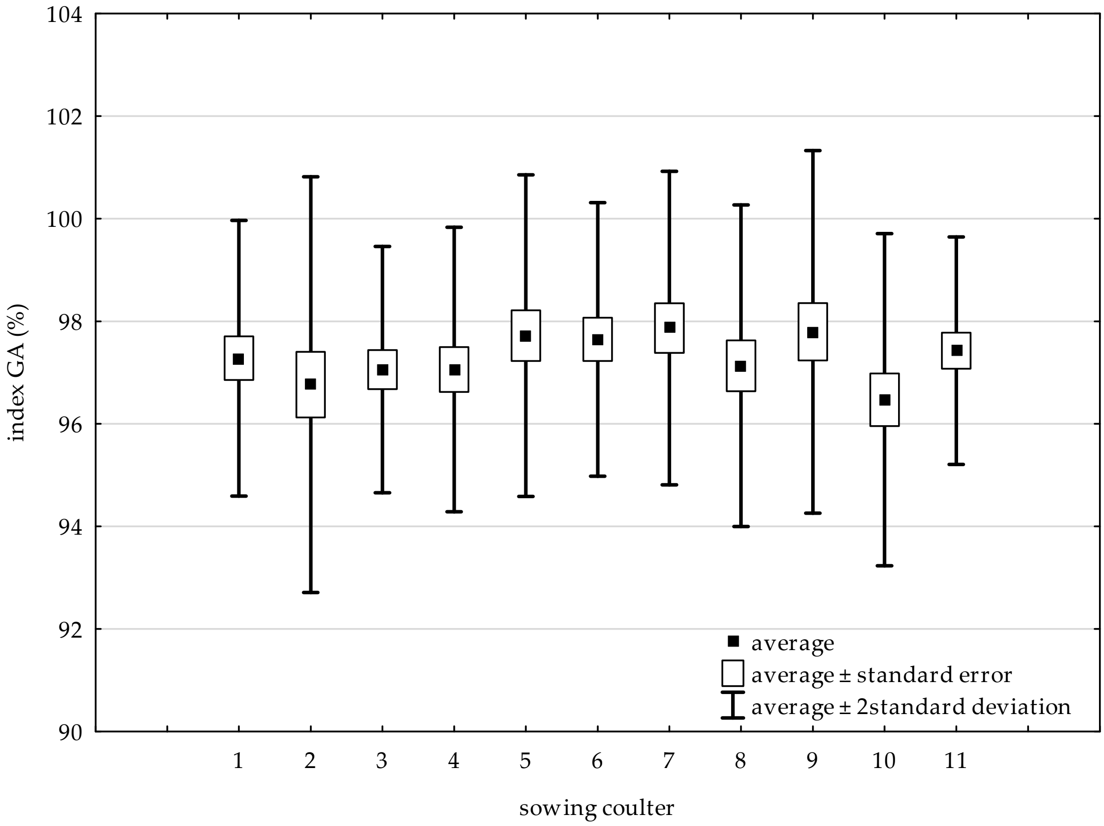


Figure 6. Grain sowing accuracy index (GA) of individual sowing coulters in laboratory tests.

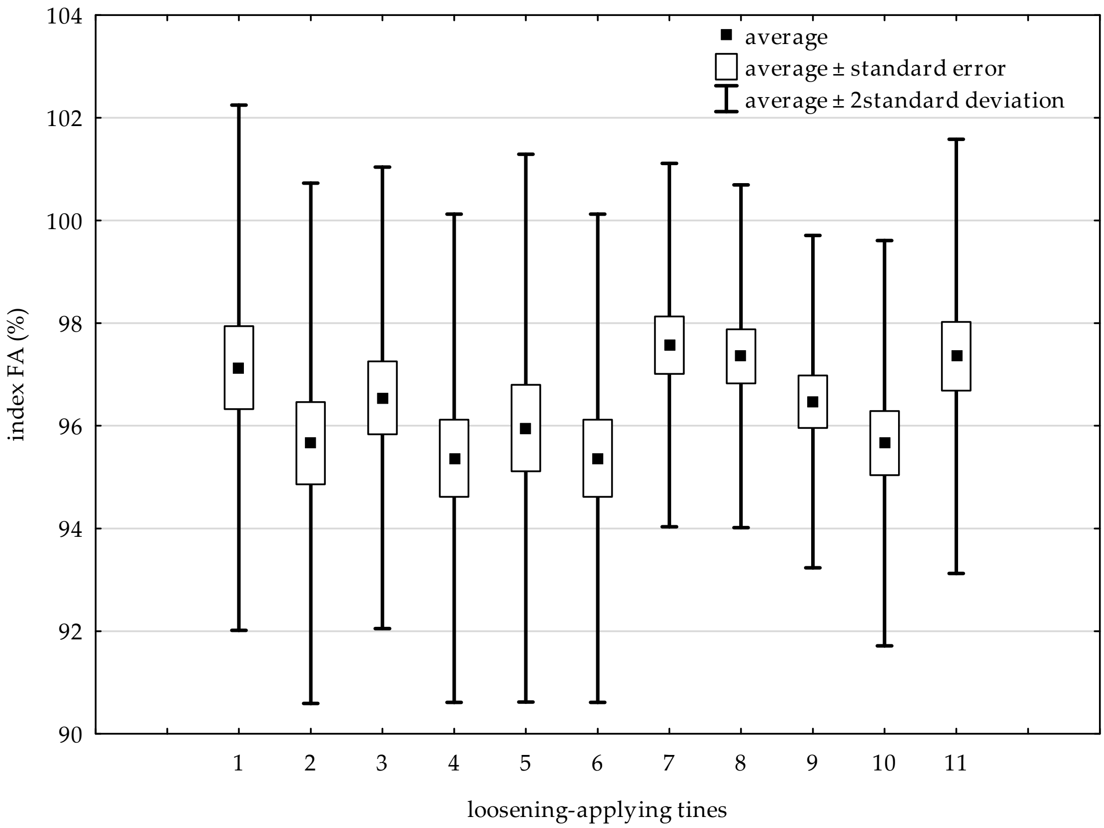


Figure 7. Fertiliser application accuracy index (FA) of individual loosening-applying tines in laboratory tests.

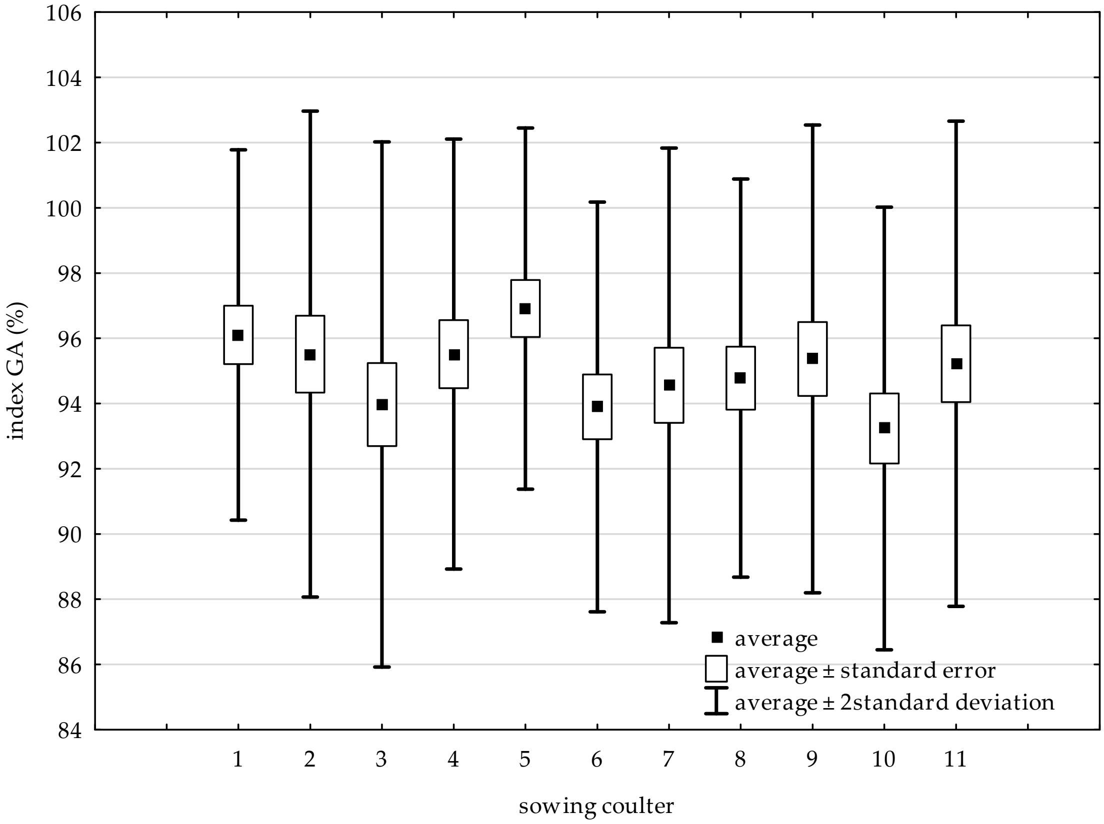


Figure 8. Grain sowing accuracy index (GA) of individual sowing coulters in field tests.

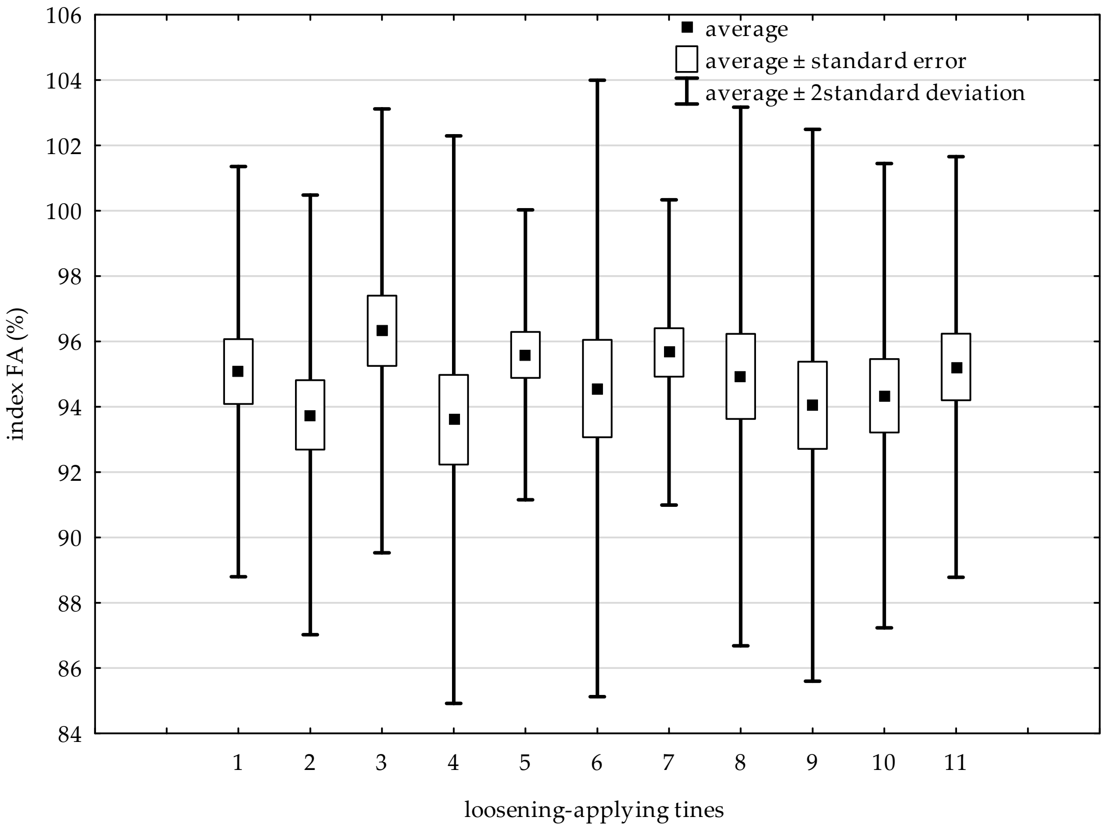


Figure 9. Fertiliser application accuracy index (FA) of individual loosening-applying tines in field tests.

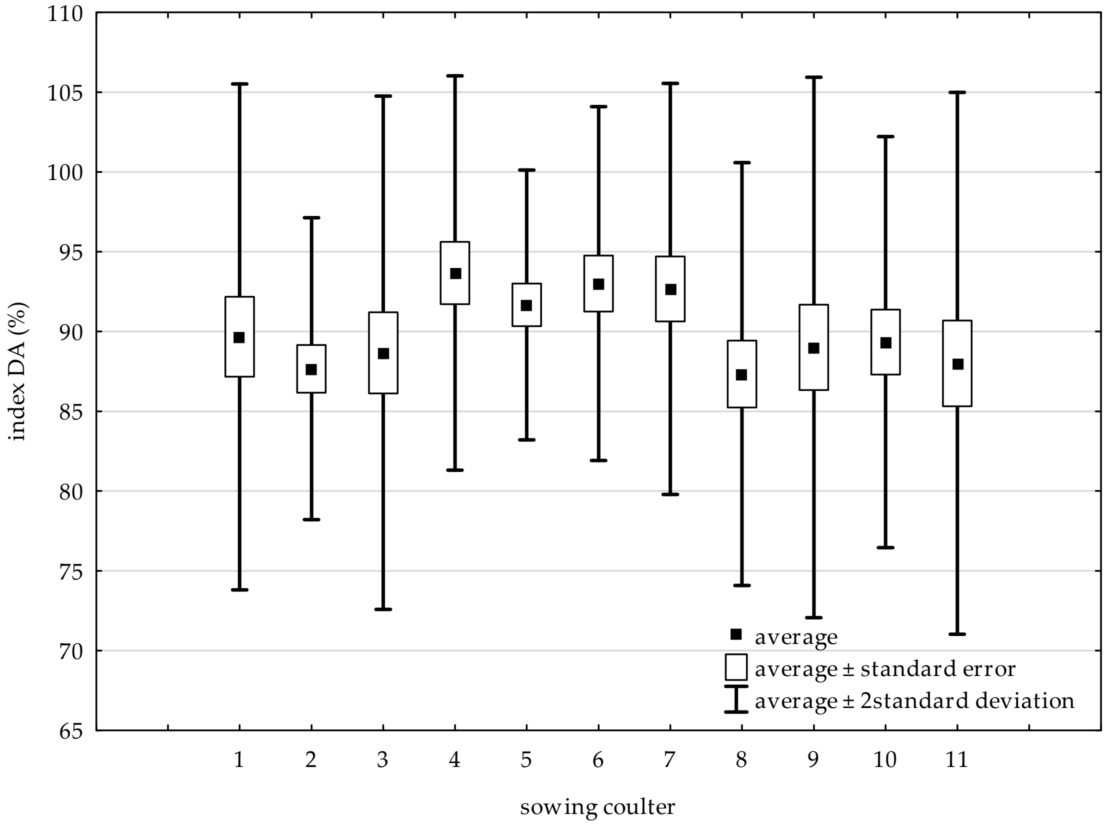


Figure 10. Sowing depth accuracy index (DA) of individual sowing coulters in field tests.

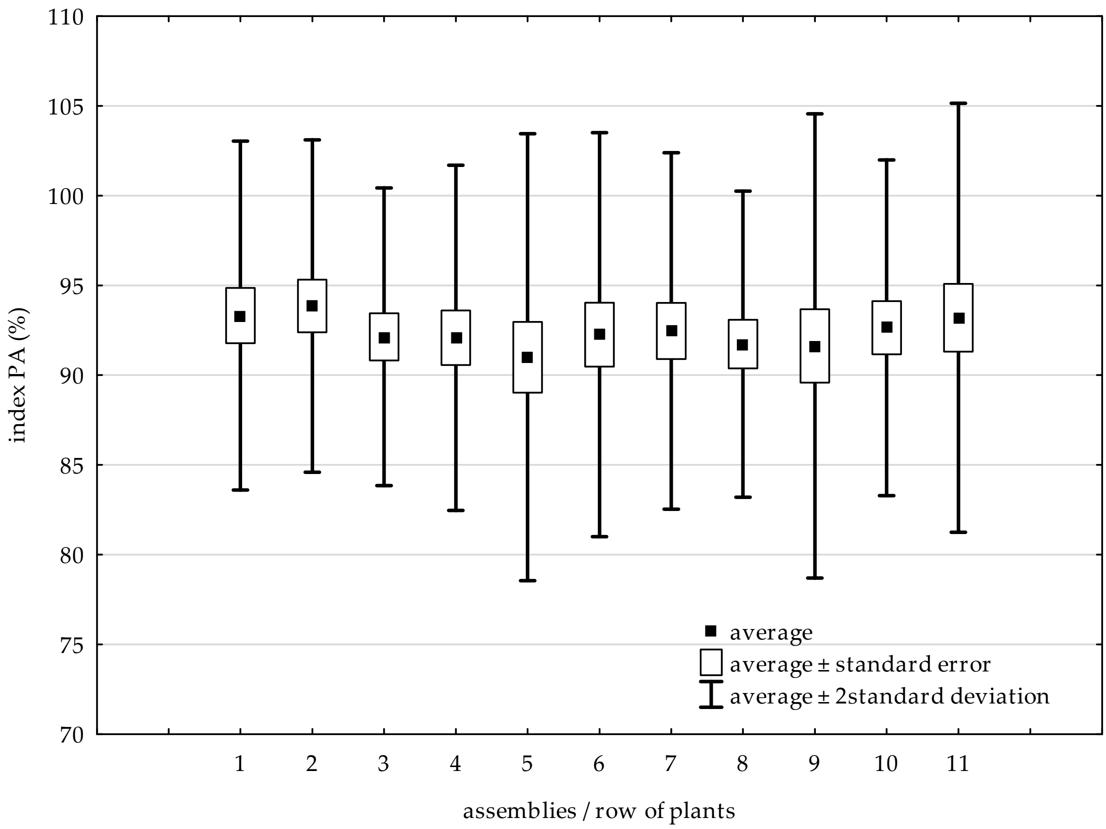


Figure 11. Number of plants accuracy index (PA) in the 11 individual rows.

Comparison of the average accuracy indices of each operating parameter of the entire machine indicates that, in field conditions, they differed only slightly from laboratory measurements. The difference for sowing accuracy (GA) and fertiliser application (FA) was 0.53 pp (percentage points) and 2.69 pp, respectively (Table 3). The least accurate operating parameter of all assemblies within the working width of the machine was sowing depth (DA = 92.00%). The CV coefficient of precision indices of sowing parameters assessed in the laboratory was below 1.00, whereas in field tests it ranged from 1.30% (sowing grain—GA) to 2.58% (sowing depth—DA).

Table 3. Accuracy indices (%) of the strip-till machine operation—average results of all seeding coulters and loosening-applying tines.

Index	Average	Minimum	Maximum	Standard Deviation	Coefficient of Variation (%)	Standard Error
Laboratory tests						
Sowing grain—GA	97.44	96.59	99.53	0.83	0.86	0.26
Fertiliser Application—FA	99.21	98.40	99.67	0.43	0.43	0.14
Field tests						
Sowing grain—GA	96.91	95.19	98.80	1.25	1.30	0.40
Fertiliser application—FA	96.52	92.78	99.67	2.32	2.40	0.73
Sowing depth—DA	92.00	87.88	96.36	2.37	2.58	0.75
Number of plants—PA	98.05	94.84	99.90	1.52	1.55	0.48

The analysis of the variability of all measurements of a given machine operation parameter (n = 110, 11 assemblies × 10 repetitions) indicates that, in laboratory tests, the rate of grain sown was more stable (i.e., a lower CV value) than the rate of fertiliser applied (Figure 12). The variability of fertiliser application rates was similar in the static laboratory tests as in the field studies. The difference in CV was 0.92 pp. In field conditions, the least stable parameter (CV = 9.83%) was sowing depth.

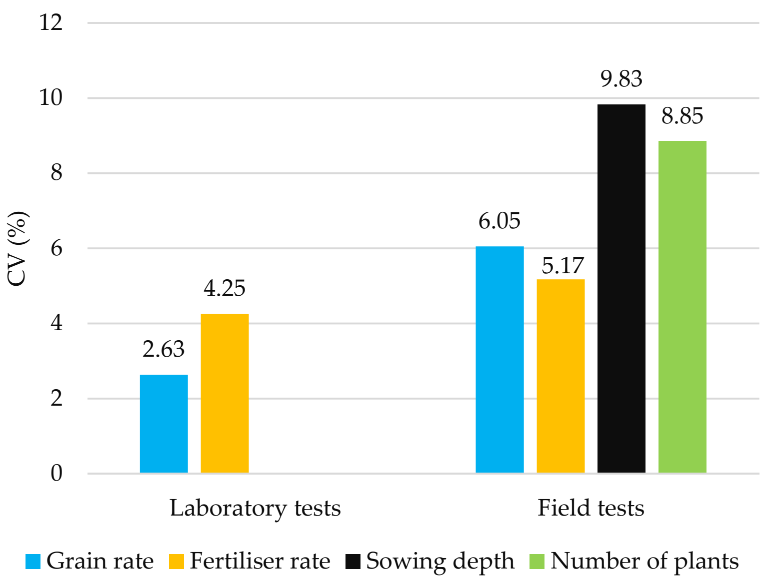


Figure 12. Coefficient of variation (CV) of the results of the machine operation parameters (n = 110, 11 assemblies × 10 measurements).

4. Discussion

Well-planned and well-executed sowing results in precise and uniform distribution of seeds in rows with the optimal spacing and appropriate depth for the plant species [46]. Sowing is a basic feature of agricultural technology that shapes the structure and architecture of a crop canopy. The construction of the seed drill, its operating parameters and their monitoring determine the uniformity of the horizontal and vertical distribution of seeds in the soil, which determines the living area of the plants [47,48]. In turn, the size of living space afforded to each plant influences the microclimate in the canopy, the efficiency of photosynthesis and, consequently, the yield [49]. This is equally important in the cultivation of crops sown in wide or narrow row spacing, e.g., cereals [50,51]. Zhai et al. [52] used a broadcast seeder to sow wheat with the theoretically most uniform grain distribution on the field surface and obtained more stalks per unit area without reducing the number of grains per ear and the thousand-grain weight than when sowing in rows. Greater uniformity of plant distribution in the canopy resulted in higher LAI, dry matter accumulation and grain yield.

The improvement of seed drills, often with the possibility of simultaneously tilling the soil and applying fertilisers, is an example of technological progress in agriculture. The assumed and expected result of new solutions is to improve the accuracy and uniformity of seed and fertiliser distribution in the soil, even in difficult field conditions. Automating and computerising these machines' management processes increases their efficiency and improves the quality of work [53,54]. Such activities also concern the construction of strip-till machines and their testing in field conditions [33]. These goals were adopted when designing the Mzuri one-pass strip-till machine. It ensured high process quality through its: pneumatic grain- and fertiliser-distribution heads for the coulter and loosening-applying tine elements with flow sensors in the transport ducts; electro-hydraulic smooth adjustment of working depth of the loosening/fertiliser-placement tines and sowing coulters with real-time parameter monitoring; ground-following, soil-consolidating wheels in the seed-sowing zone whose pressure force depends on soil properties (texture, moisture). In field conditions, the amount of wheat grain sown using the machine did not differ significantly from the theoretical amount assumed in accordance with the sowing standard, and the fertiliser dose was about 5.5 kg/ha higher than the assumed dose of 150 kg/ha. Cujbescu et al. [55] defined the sowing accuracy as the ratio of correctly sown seeds to the total expected number of seeds to be sown and obtained an index of 95.4% in a stationary test without vibration of the device and a CV coefficient of 9.1%. In field conditions, this rate was lower and the CV was higher, at 92.5% and 12.9%, respectively. The accuracy of sowing in the field deteriorated with increasing machine operating speed. Xiong et al. [56], referring to the GB/T 6973-2005 standard [57] assumed the "qualified index" as a measure of sowing accuracy. The standard assumes that the failure to place a seed where it should be sown is called a "missed sowing" (assessed using the "missed index"). It is also considered to be a missed sowing when the distance between successive seeds is greater than 1.5 times the theoretical (assumed) distance. The placement of two or more seeds instead of the intended one is called a "replay sowing" (assessed using the "replay index"). It is also considered to be a replay sowing when successive seeds are placed at a distance of less than or equal to 0.5 times the optimal distance. Therefore, sowing is "qualified" when individual seeds are spaced from each other within 0.5–1.5 times the theoretical distance. The authors, testing a newly designed mechanical-pneumatic sowing device in laboratory conditions, found that, for seeds of various sizes and properties (soybean, corn, rapeseed), the certified sowing rate exceeded 85%, and the missed sowing rate was below 10%. In our own research, the sowing accuracy (GA) index referring to the proportion of sown and unsown seeds used for laboratory testing of the designed Mzuri multifunctional hybrid machine was 97.4%, and in field conditions it was 96.9%.

Modernly designed pneumatic seed drills for precise grain sowing, which are limited by their low operating speed, nevertheless make it possible to achieve high-quality sowing. In the study by Fang et al. [58], this quality was described by a qualified sowing index of 91.66%, a replay sowing index of 5.98% and a missed sowing index of 2.36%. Sowing precision assessment indices are similarly created and calculated in accordance with the ISO 7256/1 [59] standard. The qualified seeding index and its coefficient of variation were used by Kamgar et al. [60] to evaluate the quality of work of a newly designed seed metering unit driven by a DC motor and equipped with digital encoders to monitor the rotational speed of the drive wheel. The used sowing unit improved the uniformity of wheat grain distribution in the soil compared to a traditional one. The coefficient of variation decreased from 4.40% to 1.84% at a working speed of 8 km/h and 50% plant residues in the field. The coefficient of variation in the sowing accuracy index of the Mzuri machine simultaneously tilling soil strips, applying fertilisers and sowing seeds in the laboratory and field tests was 0.86% and 1.30%, respectively. It is particularly difficult to achieve sowing precision (including accuracy of intended sowing rate and depth) in reduced-till conditions with a large amount of plant residues on the field surface. Xi et al. [61] improved the accuracy of wheat sowing by changing the design of the seeder by eliminating the tubular grain transport duct. While testing the prototype solution in the laboratory, a sowing accuracy of 83.84% was achieved. The coefficient of variation in seeding uniformity was 14.68%. In field conditions, these indicators were 83.13% and 15.12%, respectively, and the accuracy of the assumed sowing depth was 83.13%. The amount of grain sown by each coulter also depends on the position of the outlet relative to the grain tank [62]. In our own research, on average, each of the three outer coulters of the Mzuri machine (the furthest from the grain tank) tested in field conditions sowed 13.48 kg of grain. Meanwhile, each of the five middle coulters sowed 13.76 kg of grain.

The optimal and uniform sowing depth determines the uniform development of plants in the field, starting with germination and emergence. This sowing parameter is difficult to achieve, however, due to spatial variation in soil conditions within the field. Manually adjusted coulter pressure does not take into account variations in soil resistance during work. That is why modern solutions, including the developed Mzuri machine, have assemblies that dynamically adjust coulter load and depth of work. Such designs are used in modern sowing units of agricultural machine. They allow automatic adjustment of operating parameters depending on changing conditions within the field or between different fields. Sowing depth and the pressure force of the compaction wheel adapt to the field shape or soil moisture [63]. In studies by Nielsen et al. [64] and Nielsen et al. [65], it has been shown that such solutions improve the accuracy of seeding depth. Assuming a wheat sowing depth of 30 mm and a sowing speed of 8 km/h, the average deviation from this value was 5.3 mm—compared to 9.1 mm with traditional control. However, significant differences were found in the working depth of each of the eleven assemblies across the working width of the machine. The working depth range of the assemblies was from 14.2 mm to 25.9 mm. Sowing depth can also be better equalised by sowing assemblies equipped with a magnetorheological damper. A machine designed for ploughless sowing and equipped with a damper placed wheat grain at a depth of 39.8 mm, compared to the assumed 40 mm. The standard deviation of this sowing parameter was 5.8 mm and the coefficient of variation was 14.6% [66]. Field tests of the developed Mzuri machine have shown that the strip-till one-pass technology can sow wheat with a depth accuracy (DA) of 92.0% at a CV of 2.58%. At the same time, the variation in the working depth of the 11 assemblies across the working width of the machine did not exceed the limits from a minimum of 22 mm to a maximum of 33 mm with the assumed optimum size of 30 mm. The emergence capacity of wheat sown in strip-till technology using the newly designed machine was 88%, which is a very good result in conditions of a large amount of plant residue on the field surface and the lack of prior seedbed preparation. Research Carman et al. [67] indicate that the ability of plants to emerge depends on the design of the elements loosening the soil strips and sowing the seeds. In the cited studies, the ability of corn to emerge, depending on the machine used, ranged from 80.0 to 89.5%.

Equally important in modern agricultural technology equipped with real-time monitoring and control systems for working elements are seed drills that can apply fertilisers [68,69]. Yu et al. [70] indicate that, in a seed-fertiliser drill machine with fluted rollers, the dosing elements and systems adjusting their operation to environmental conditions and their degree of wear can maintain high precision of both seed sowing and fertilisation. According to the authors, the average relative deviations between actual and assumed (theoretical) application rates were 0.97% for wheat grain and 1.22% for fertiliser. The corresponding standard deviations were 0.69% and 0.62%. In turn, Yu et al. [71] assessed the precision of sowing and fertilisation based on real-time online measurements of grain and fertiliser mass and found that, in an area of 2.5 ha, the relative error of the cumulative application rate was 4.88%, and the mean error was 2.62% with a standard deviation of 1.7%. The average error in measuring the dynamic application rate on an area of ~2.2 ha was 3.15% with a standard deviation of 1.64%.

The key structural and functional element responsible for the uniformity of seed sowing and fertiliser application by individual assemblies of the machine is the dosing device. Adilet et al. [72] showed that replacing grooved devices with a pin-roller device increased the uniformity of sowing wheat grain and granular fertiliser. For wheat grain sowing, the CV was 96% and 37% for a twelve-grooved and roller-pin type, respectively, and for fertiliser distribution it was 80.74% and 37%. The authors of the paper, examining the accuracy of fertilisation by the 11 assemblies of the Mzuri machine in ten places on a 2.5 ha field, found that the average CV of the applied fertiliser dose was 2.52%, which was 1.68 pp higher than the static laboratory test results.

5. Conclusions

The expectations placed on the modern agricultural machine and equipment market are being met by industry and science. Cooperation among these areas of economic and social activity is particularly valuable. New technical solutions in agriculture should fit into the generally accepted direction of development of societies, e.g., Industry 4.0, Agriculture 4.0. In the field of plant cultivation, the strip-till one-pass technology is developing dynamically. It relates to the principles of conservation agriculture, which is environmentally friendly while maintaining its socio-economic role. The designed machine performs simultaneous tillage of soil strips, fertilisation and sowing and is equipped with a central computer that, through working assemblies, manages seed transport, sowing quantities, sowing depth, the pressure force of the ground-following/soil-consolidating wheels, and fertiliser dosing to implement its improvements in agricultural technology. The machine provides high-quality sowing and fertilising. The results of static laboratory tests were confirmed by tests under field conditions. The accuracy of the sowing amount, sowing depth and fertiliser dose of not less than 92% enabled uniform plant emergence—number of plants in a row (CV 1.55). The machines provision of an 88% field wheat emergence capacity resulted in a very good (expected) plant density. In turn, the uniform operation of all eleven assemblies in terms of rate of seed sown, sowing depth and fertiliser application results in the crop being uniform in the field space after emergence. The multifunctional Mzuri machine with automatic regulation and real-time monitoring of operating parameters, although it requires further research and technical improvement, is a significantly addition to the innovative agricultural machines on the global market. Further research should focus on improving sensors for assessing environmental properties in order to use the data for real-time machine control.

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