

Article

Speed and Depth Effects on Soil Fragmentation, Non-Chemical Weed Control, and Immediate Crop Damage During Mechanical Weeding in Wide-Row Wheat

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Abstract

Mechanical weed control is a crucial sustainable alternative to chemical herbicides, yet optimising implement parameters to balance non-chemical weed suppression with crop safety remains challenging. This study evaluated how forward speed and working depth influence soil fragmentation, weed control efficacy, and immediate plant injury during the mechanical weeding of wide-row wheat. Field experiments tested three tractor speeds (6, 9, and 12 km·h^{−1}) and two working depths of duckfoot sweeps (30 and 50 mm). Key indicators—including the degree of soil crumbling, mean clod diameter, weed control effectiveness, and crop injury rates—were evaluated using analysis of variance. Higher speeds increased soil crumbling and reduced clod size, whereas effective weed destruction depended primarily on depth. Working with duckfoots at 50 mm achieved 95.9% weed removal efficiency, outperforming the 30 mm depth (80.2%). However, increasing speed above 9 km·h^{−1} caused a sharp rise in the immediate crop injury rate (reaching 26.8%), while direct plant cutting remained low. This indicator represents visible post-treatment injury and should not be interpreted as irreversible crop loss or yield reduction. These findings demonstrate an asymmetric impact of operating parameters: deeper depths maximise weed clearance, but excessively high speeds severely increase crop damage. Optimising these settings is vital for sustainable field operations and underscores the need for improved implement designs to minimise lateral soil discharge.

Keywords: non-chemical weed management; sustainable agriculture; wide-row cultivation; duckfoot sweep; soil fragmentation; mechanical crop damage



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1. Introduction

Modern agriculture continues to strive to limit the use of chemical plant protection products, driven by both growing environmental pressure and restrictive legal regulations [1]. Mechanical methods, although historically well known, are currently experiencing a technological renaissance because they prevent weeds from becoming resistant to active substances and can be effectively integrated into organic and precision farming systems [2]. To meet the stringent requirements for treatment accuracy in crop fields, modern aggregates, including row cultivators, are increasingly equipped with automatic vision-guidance systems and GPS-based control [3,4]. Such innovations enable real-time correction of the driving path and safe mechanical weeding with narrow protective strips, without a significant decrease in crop productivity [5]. But even with advanced control,

the physical interaction of tools (such as duckfoots or blades) with the soil in the intra-row and inter-row zones requires careful management of treatment intensity [6] to prevent mechanical damage or crop uprooting [6].

The quality of mechanical weeding depends on the precise selection of the machine's operating parameters, which should, on the one hand, ensure high weed control efficiency and, on the other hand, protect the crop. Key operating factors include the unit's speed and the working depth of the working elements, such as the duckfoot. The processes of interaction between these tools and the soil are the subject of advanced analyses using empirical [7], analytical [8], numerical [9], and hybrid models [10]. Duckfoot resistance simulations unequivocally confirm a nonlinear increase in drought force with increasing tool width and working depth [11,12]. Numerical studies have also shown that changing the dimensions of working elements affects the kinematics of movement of individual soil particles. The greatest longitudinal deformations occur along the axis of the tool's trajectory, and the smaller wings of the duckfoots produce stronger vertical displacements [13]. Diverse soil deformations under duckfoot pressure result in different effects on weed removal and crop backfilling. Field and model studies thus confirm that the selection of operating parameters significantly affects the intensity and degree of soil crumbling [14], which in turn affects the destruction of weed root systems [14], while also creating optimal conditions for the main crop [15]. At the same time, excessively high speeds can lead to undesirable phenomena such as lateral movement of the machine [16], soil wedges being thrown back, backfilling rows, or direct damage to crops [17]. Exceeding the speed limits intensifies the lateral rejection of cut soil, making it easier to throw weeds out. Still, it also leads to unacceptable backfilling of protected plant rosettes, especially in the early stages of their development [18]. Wide-row and banded-row cereal systems create an inter-row zone that mechanical weeding tools can access after crop emergence. Such systems may support non-chemical weed management by combining crop competition within the sown bands with physical weed disturbance in the wider inter-row strips. Previous studies have shown that the efficacy of inter-row cultivation in cereals depends on crop and weed developmental stages, row geometry, soil conditions, working depth, and travel speed. Although wider inter-row spacing can facilitate mechanical weed control, operational settings must be carefully selected because increased soil displacement may improve weed suppression but also increase the risk of soil burial or mechanical injury to crop plants [6,14]. Despite extensive research, weeding machines and weed-removal components are still being improved as the state of the art advances and the user experience of agricultural technology improves.

The study aimed to assess the impact of the speed and working depth of duckfoot cultivators on the soil environment, plant care, and crop protection. The main research problem is reduced to the question: how does the relationship between the tool's speed and working depth determine the balance between the effectiveness of soil loosening and weeding and the risk of crop damage? Based on this problem, two explanatory hypotheses were formulated.

H1. *Depth and working speed have an asymmetrical effect on the efficiency of the cultivator, as depth determines the effectiveness of weed destruction by cutting and turning over a larger soil mass, while speed affects the degree of soil crumbling, assuming that the higher kinetic energy transferred by the tool to the soil clods facilitates the overcoming of cohesion forces, leading to structural cracking.*

H2. *When the critical working speed is exceeded, there is a rapid increase in crop backfilling, as the excessive dynamics of the lateral ejection of the soil through the duckfoot's wings and the vibrations of the sections break the physical function of the side discs covering the crops.*

The scientific innovation of this study lies in bridging the gap between theoretical soil interactions and actual agronomic field performance. The study provides crucial empirical evidence on the effects of changes in ground speed and working depth on the dynamic and kinematic phenomena that govern soil fragmentation and lateral discharge during duckfoot sweeps. By quantifying these real-world effects, this study demonstrates the fundamental trade-offs between maximising weed control and minimising direct crop damage in wide-row systems.

2. Materials and Methods

2.1. Characteristics of the Test Object

To achieve the research objective, an exemplary mounted row cultivator with a working width of 9 m was used for mechanical weed control in wide-row and narrow-row crops (Figure 1). The machine was equipped with independent working sections, each with its own copying wheels, suspended on articulated parallelograms with double control arms. This ensured precise copying of uneven terrain and maintained a constant, preset working depth for each section, regardless of the support frame's vertical movement.



Figure 1. Mounted in-line cultivator at the front of a tractor, prepared for field testing.

Each weeding section is equipped with three flexible tines (Vibro Crop type, VCO), completed duckfoots with a working width of 135 mm (Figure 2).



Figure 2. View of the weeding section equipped with three duckfoots and two shields covering the rows of plants (shows how to set the working depth).

In the kinematic system, the middle duckfoot tool was located on the section axis. In contrast, the two side tools were mounted 100 mm apart from the axle, providing good coverage of adjacent weeding tracks. To prevent crops from being backfilled with discarded soil, 350 mm spacing shields were installed at the side-cutting elements, maintaining a

75 mm-wide protective strip on each side of the plant row. The cultivator was operated by an agricultural tractor with a power of 86 kW. The basic technical and operational parameters of the tested row cultivator are listed in Table 1.

Table 1. Selected technical parameters of the row cultivator.

Technical Parameter	Unit of Measurement	Face Value
Machine type	-	Suspended on the front linkage (category 3)
Total machine weight	kg	2769
Maximum working width	mm	9000
Dimensions in working position (L × W × H)	mm	3455 × 9767 × 1750
Dimensions in transport position (L × W × H)	mm	3325 × 2980 × 3540
Maximum working depth	mm	70
Working width of duckfoot	mm	135

2.2. Field Conditions and Soil Parameters

Field research was carried out at the Agricultural Experimental Plant of the Warsaw University of Life Sciences, Wilanów-Obory, on a winter wheat plantation, sown in rows with a spacing of 25 and 50 cm, on a plot of 350 m × 35 m. The wheat was established in a banded row arrangement, with two crop rows spaced 25 cm apart and a 50 cm inter-row strip between successive crop bands. Mechanical weeding was conducted exclusively within the 50 cm inter-row strips; the 25 cm crop bands were not treated. The same operator performed all operations to minimise variability associated with machine guidance and row tracking. The winter wheat was at the tillering stage during the field experiment. Before proceeding with the actual operational tests, the soil's physical condition was characterised in detail, including its moisture content, penetration resistance (compactness), and bulk density.

The moisture content of the soil (sandy loam) profile was determined by the dryer-weight method, taking samples in the morning before the start and in the evening after the end of the experiments, in accordance with ISO 11465 [19]. The samples were weighed with an accuracy of 0.01 g on the WPS 600/C balance (RADWAG, Radom, Poland). Soil samples were dried in a laboratory dryer (SLW 115, Pol-Eko Aparatura, Wodzisław Śląski, Poland) at a temperature of 105 ± 2 °C for 24 h. Five moisture content determinations were made for each condition.

Soil penetration resistance (expressed in kPa) was measured to a depth of 150 mm using a conical penetrometer with a 30° opening angle and a base diameter of 20.27 mm, as specified in ASAE S 313.3 [20]. Along the plot at distances of 50, 100, 150, 200, 250, and 300 m from the beginning of the field, 6 randomly selected locations were designated across the width of the field plot, and four measurements were taken in each of them.

The bulk density of the soil was determined intact using an Eijkelkamp cylindrical sampler (Royal Eijkelkamp, Giesbeek, The Netherlands) type 04.17 with a height of 50 mm and a volume of 100 cm³. Six samples were taken from a randomly selected inter-row area to a depth of 150 mm. The samples were weighed to an accuracy of 0.01 g on the WPS 600/C balance (RADWAG, Radom, Poland).

Weed infestation in wheat cultivation was determined at 50 randomly selected locations within a separate research plot. Weeds were pulled from the surface of a 1 m² frame, counted, and weighed together on a WPS 600/C scale (RADWAG, Radom, Poland) with

an accuracy of 0.1 g. The average number and weight of weeds per 1 m² were determined. The dominant weeds in the wheat field were: white goosefoot (*Chenopodium album* L.), field pansy (*Viola arvensis* Murr.), silky bentgrass (*Apera spica-venti* L.), meadow foxtail (*Alopecurus myosuroides* Huds.), cleavers (*Galium aparine* L.), and common chickweed (*Stellaria media* (L.) Vill.).

2.3. Experimental System and Measurement Method

The field experiment was planned as a full orthogonal design, with operating depth and aggregate movement speed as independent variables. The tests were carried out at two working depths of duckfoots (30 mm and 50 mm) and three tractor speeds (6, 9, and 12 km·h⁻¹). The working depth was checked at 30 locations after removing loose soil from the worked strip. The measurements were made with a depth gauge accurate to 1 mm. For the assumed working depths of 30 mm and 50 mm, the measured groove depth values were 30 ± 3 mm and 50 ± 2 mm, respectively. The reported depth values represent measurements obtained at the designated control locations and do not constitute a continuous record of transient depth fluctuations during each pass. Therefore, short-term changes in depth caused by frame vibration or section dynamics could not be quantified in the present field experiment. The speed of the tractor-cultivator was calculated from the recorded travel time with a stopwatch, with an accuracy of 0.01 s over a 30 m section measured with a linear gauge, and an accuracy of 1 cm per setting variant. For the assumed movement speeds of 6, 9, and 12 km·h⁻¹, the actual values were 5.66 ± 0.11 km·h⁻¹, 8.76 ± 0.18 km·h⁻¹, and 12.29 ± 0.26 km·h⁻¹, respectively.

For each setting variant (depth, speed), at least 5 independent measurement repetitions were performed at randomly selected control points. To assess the degree of soil crumbling (K_c in %), a 1 m² frame was used, and all other clods with a diameter exceeding 30 mm were collected from it. The collected soil aggregates were counted, measured with a calliper with an accuracy of 1 mm, and weighed on a WPS 600/C laboratory balance (RADWAG, Radom, Poland) with an accuracy of 1 g, which allowed the calculation of the percentage of clodding index and the average weighted diameter of the clods (d_c in mm, Table 2). Sieve analysis was not used to determine the particle size distribution because attempts to use it resulted in fragmentation of the solids. Based on the number and weight of soil clods, clodding after weeding was calculated for a 1 m² area using the average clod weight and its standard deviation. Because the collected clods were irregular and non-spherical, the measured dimension should be interpreted as an operational clod-size indicator rather than a true geometric diameter. This approach was adopted to maintain comparability with sieve-based size classification, in which the limiting dimension determines whether a clod can pass through a given opening. A three-dimensional characterisation would be more precise, but was outside the scope of the present field protocol.

The weed control efficiency index (W_{ce} , %) was also determined using the frame method by comparing the number of weeds in a randomly selected 1 m² area before the unit passed and immediately after treatment in the same area. Since a 75 mm protective strip is used on both sides of the rows, the weed control rate calculated this way does not reflect the actual duckfoot effect during weeding. To present the effects of directly cutting weeds from the area being worked through the cultivar sections, an inter-row weed removal efficiency (W_{ire} in %, Table 2) was introduced.

At the same time, the treatment's negative effects on the main crop were assessed. On randomly designated sections of 1 m of the running row of plants, the initial planting of wheat was counted. After the treatment, the number of plants completely cut down was documented to determine the C_{ur} rate in %; the number of plants mechanically damaged (bent, broken) and covered with discarded soil, mainly by external duckfoots tools, in the

section (C_{ibr} rate in %). The obtained values were used to calculate the percentage losses in wheat cultivation. Crop injury was assessed immediately after the weeding operation and therefore represents visible short-term mechanical injury. The assessment did not determine whether bent or partially buried plants subsequently recovered. Accordingly, the crop injury rate should not be interpreted as an estimate of irreversible plant loss or yield reduction. Further observations after the treatment would be required to distinguish transient injury from irreversible damage and to quantify effects on subsequent biomass accumulation or yield.

Five basic indicators that reflect the machine's impact on soil, weeds, and the main crop will enable an objective assessment of the selected operating parameters and the quality of the cultivator's work. The highlighted indicators, along with their corresponding equations and explanations, are listed in Table 2.

Table 2. Overview of the measured quality indicators of the row cultivator.

Work Quality Indicator, Symbol, and Unit	Analytical Dependency and Explanation of Variables
Degree of soil crumbling, K_c (%)	$K_c = 100(1 - A_c)$, where A_c is the area occupied by clods with a diameter of more than 30 mm collected from an area of 1 m ² .
Mean soil clod diameter d_c (mm)	$d_c = \sum_{i=1}^n \left(d_i \frac{m_{ci}}{m_{ct}} \right)$, where d_i is the diameter of a single clod, mm; m_{ci} is the mass of a single clod d_i , g; m_{ct} is the total mass of all clods collected from an area of 1 m ² , g.
Weed control efficiency, W_{ce} (%)	$W_{ce} = 100 \frac{W_t - W_s}{W_t}$, where W_t is the initial number of weeds in an area of 1 m ² before treatment; W_s is the number of weeds that survived the treatment.
Inter-row weed removal efficiency, W_{ire} (%) (excluding protective zones at plant rows)	$W_{ire} = 100 \frac{W_{irt} - W_{irs}}{W_{irt}}$, where W_{irt} is the initial number of weeds in the weeding zone (strip) before treatment; W_{irs} is the number of weeds in the weeding zone that have not been shaken out of the soil.
Crop uprooting rate, C_{ur} (%)	$C_{ur} = 100 \frac{C_t - C_r}{C_t}$, where C_t is the total initial number of plants per 1 m of the current row; C_r is the number of wheat plants left after the treatment.
Crop injury rate, C_{ibr} (%)	$C_{ibr} = 100 \frac{C_t - C_{cb}}{C_t}$, where C_t is the total initial number of plants per 1 m of the current row; C_{cb} is the sum of plants mechanically damaged (cut, broken/bent) and completely covered with soil on a section of 1 m of the current row.

2.4. Statistical Analysis

Before ANOVA, the assumptions required for parametric analysis were considered. Independence of observations was ensured by the experimental design, as treatment replicates were conducted independently and measurement locations were randomly selected. For each dependent variable, the Kolmogorov–Smirnov (K-S) test with the Lilliefors correction (K-S-L) and the Shapiro–Wilk (S-W) test were used to assess the conformity of the distributions to a normal distribution. Based on the K-S test results, the variable distributions are, in most cases, not significantly non-normal. The results of the Levene and Brown–Forsyth tests also, in most cases, do not provide grounds for rejecting the hypothesis of homogeneity of variance between the analysed groups. Only the inter-row weed removal efficiency (W_{ire}) and the crop uprooting rate (C_{ur}) require caution in their interpretation, as the assumptions have not been met, especially for operating systems at higher movement speeds of 9 and 12 km h^{−1} ($p < 0.05$). With this consideration, it was decided to use a parametric statistical analysis.

Two-way ANOVA was then performed to evaluate the effects of nominal forward-speed level, working-depth level, and their interaction on the measured quality indicators. When ANOVA indicated statistically significant differences among treatment means, Tukey's honestly significant difference (HSD) post hoc test was applied for multiple comparisons. Correlation relationships between factors and parameters were determined using the Pearson correlation test, and descriptors were used to interpret the correlation coefficients [21]. For variance analysis (ANOVA), the operating speeds were treated as categorical factor levels and are referred to by their nominal target values (6, 9, and 12 km·h⁻¹) for clarity. In contrast, the exact measured continuous values were applied in correlation analyses. The statistical analysis was carried out at the assumed level of significance ($\alpha = 0.05$) using Statistica v.13.3 (StatSoft Poland Ltd., Cracow, Poland).

3. Research Results and Discussion

3.1. Field Characteristics: Soil Moisture, Soil Penetration Resistance and Bulk Density, Wheat Weed Infestation, and Clodding After Weeding

The soil moisture measured in the morning at the beginning of the study was, on average, $14.74 \pm 1.28\%$. After the study (at the end of the day), the moisture content decreased to $13.55 \pm 0.68\%$. The soil condition was favorable, as it was not too plastic, and the clods broke easily in the hand under pressure.

The average soil penetration resistance for the entire field was 640 ± 146 kPa. The soil penetration resistance in individual control sections along the field plot varied randomly. Over a distance of 100–150 m from the field start, the soil was more compact, with values of 781–786 kPa and a standard deviation of 120 kPa. At a distance of 150 m from the plot boundary, soil penetration resistance was lower. It amounted to 458 ± 63 kPa, and in other areas of the plot, the penetration resistance was again higher: 607–651 kPa (SD = 86 kPa) in the last section, and at a distance of 300 m from the beginning of the plot, the soil penetration resistance was 555 ± 62 kPa. The recorded variability in soil penetration resistance across the studied field is typical of soil mosaicism, a characteristic of the Polish agricultural landscape [22], particularly in the Vistula basin, where the investigation was conducted. The natural heterogeneity of grain size and the varied loss of organic matter within the same plot cause local fluctuations in the physical structure and water-air relations [23]. In agricultural engineering, variability in soil penetration resistance poses a significant challenge, as it locally degrades the stability of the working depth of passive weeding sections [24]. The soil measurements indicated spatial variability in penetration resistance and bulk density across the field, whereas moisture was characterised before and after the experimental operation. These properties were used to describe the experimental conditions rather than introduced as independent treatment factors. Because measurements were not collected at every treatment observation point, the potential effect of microscale soil variability cannot be entirely ruled out. Therefore, the reported treatment effects apply primarily to the soil structure, moisture conditions, and field heterogeneity observed during the experiment.

The soil bulk density was 1316 ± 170 kg m⁻³ and varied slightly with depth. The lowest soil bulk density was in the shallowest soil layer (0–5 cm), averaging 1125 ± 122 kg·m⁻³, where water and air erosion occurred, loosening the soil. In the deeper layers, values increased due to soil subsidence. In the 5–10 cm and 10–15 cm layers, the bulk density of the soil was 1389 ± 64 kg m⁻³ and 1433 ± 113 kg m⁻³, respectively. The obtained bulk density distribution indicates a classic stratification of the crop field profile, in which erosion and tillage loosen the top layer, while subsidence processes thicken the deeper layers [25]. In the context of mechanical cultivator operation, this phenomenon benefits the efficiency of duckfoot tools. Low soil layer density in the 0–5 cm layer indicates low shear resistance, but

the effectiveness of weed root trimming depends on soil moisture. The elements of the tool form a soil flow that covers the weeds, but this flow also creates the risk that the rejected soil will cover the crop rows [6]. On the other hand, a higher soil density in the 5–15 cm depth range stabilises the cultivator frame's movements in the vertical plane [16,26]. It should be emphasised, however, that the soil–tool interaction and the soil fragmentation observed in our study are strictly dependent on prevailing moisture and structural conditions. These properties favoured the formation of clods of an appropriate size; however, with a different soil type (e.g., one with a higher clay content) or different moisture levels, the distribution of the tool's cutting forces and the intensity of lateral soil throw could change significantly, directly affecting weed burial efficiency and the risk of damage to crop plants.

The collected empirical data on the state of weed infestation before treatment and the structure of the remaining soil clods were illustrated using frequency analysis (Figure 3). The average number of weeds and their total weight per unit of reference area (1 m^2) were 18 pcs and 6.87 g, respectively, which determines the average weight of a single weed of 0.39 g. There was a strong right-oblique asymmetry for the number of weeds. Low-intensity communities (0–20 weeds per m^2) were clearly dominant, comprising up to 65% of the collected weeds. In subsequent density classes (20–40 and 40–60 $\text{pcs} \cdot \text{m}^{-2}$), this share decreased significantly, to 31% and 4%, respectively.

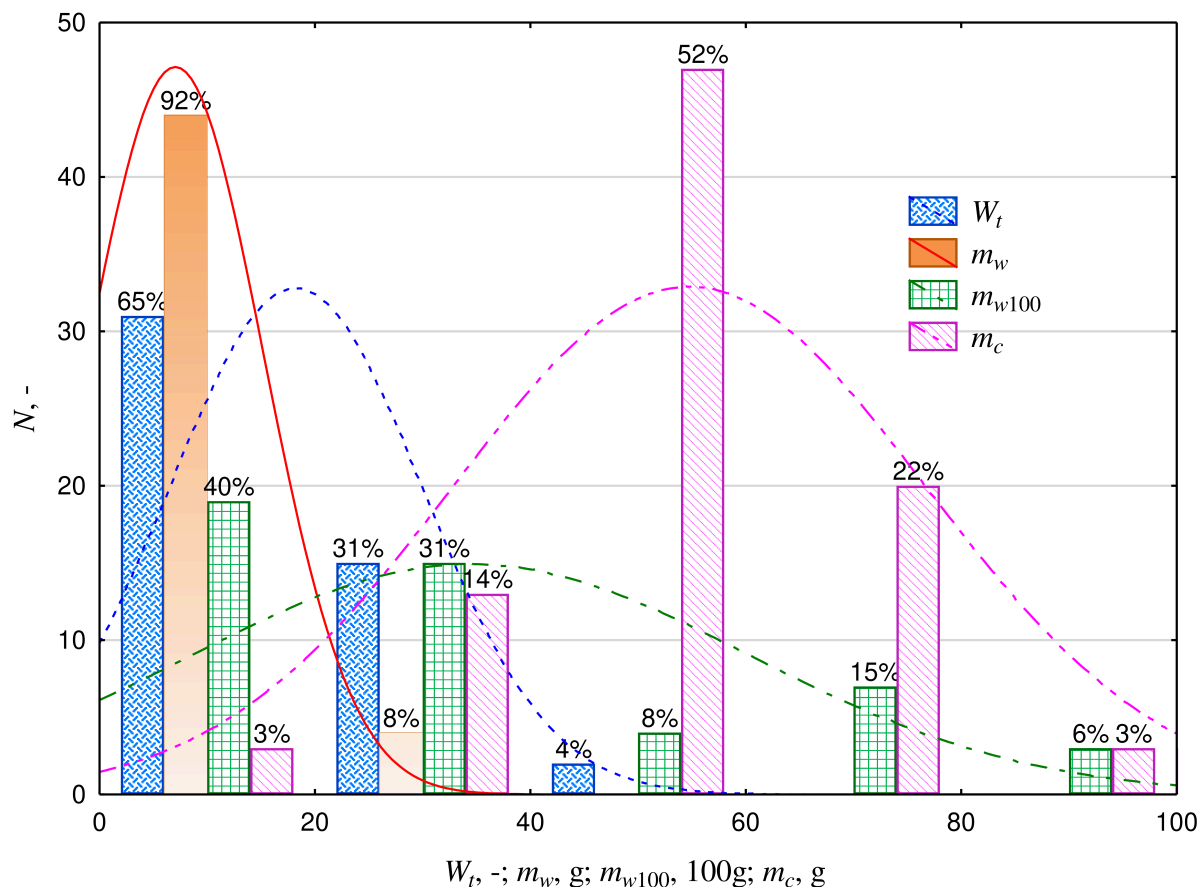


Figure 3. Histograms of the distribution of the number of weeds on an area of 1 m^2 W_t ; mass of all weeds collected from an area of 1 m^2 m_w , g; weight of a single weed m_{w100} (for the calculation of a common graph, the mass of a single weed was multiplied by 100), 100 g; mass of a single clod of soil m_c (clods collected from an area of 1 m^2), g.

Such a decomposition is characteristic of the initial phases of segetal community development, when many small seedlings are susceptible to effective destruction by early mechanical treatment [27]. The total mass of weeds collected from the studied area showed

a stronger concentration, with 92% of the recorded masses in the 0–20 g·m^{−2} range, and the remaining weed density did not exceed 40 g·m^{−2}.

The weight distribution of individual weeds, a derivative of their density, showed slightly less asymmetry. Most of the studied population (71%) were weeds in the early stages of development. In the lowest unit-weight ranges of 0.00–0.20 g and 0.20–0.40 g, 40% and 31% of plants were recorded, respectively. In subsequent weight classes (0.40–0.60 g, 0.60–0.80 g, and 0.80–1.00 g), attendance decreased to 8%, 15%, and 6%, respectively. This is a beneficial weed profile in the context of care treatments. In studies on mechanical control (e.g., the use of flexible tines and duckfoots), it has been shown that young weeds with a shallow root system and low unit weight are the easiest to undercut and cover with a thin layer of soil [28–30]. Carrying out the treatment at an early stage of weed development allows for achieving the highest weed control efficiency index [31].

In contrast to the weed parameter distributions, the mass of individual soil clods (m_c) after weeding showed a much more symmetrical distribution (like a Gaussian curve). The central value (dominant) was 40–60 g, accounting for 52% of the collected clods. The distribution was characterised by a slight right skew, with clods weighing more than the average (over 60 g) accounting for 28% of the population. In comparison, finer soil aggregates (less than 40 g) accounted for 17%. Such a shift in the distribution towards larger fractions indicates a limited impact force of elements operating at relatively deep settings and higher soil viscosity in deeper crop layers [32,33]. From an agricultural engineering perspective, this means that the observed weeding performance reflects the machine's response to the specific, mosaic-like conditions of the test field. Variations in soil texture or moisture content would result in different characteristics regarding clod fragmentation and particle flow around the spring tines. This factor represents both a natural limitation and an area for further comparative research.

3.2. Results of the Statistical Analysis

Movement velocity (v) statistically significantly differentiated among three indicators: the degree of soil crumbling (K_c), the mean clod diameter (d_c), and the crop injury rate (C_{ibr}). On the other hand, the working depth (d) significantly affected two indicators: weed control efficiency (W_{ce}) and inter-row weed removal efficiency (W_{ire} ; Table 3). The interaction between movement speed and working depth was also statistically significant, affecting changes in the crop injury rate C_{ibr} ($p = 0.0375$). However, no statistically significant influence of the main factors (v and d) or their interaction on the change in the crop uprooting rate (C_{ur}) was found.

The significance levels for the correlation coefficients between the decision variables (v , d) and the criterion indicators describing the quality of the cultivator's work coincided with those of the Fisher-Snedecor (F) test from the analysis of variance (ANOVA). The correlation coefficient between movement speed and mean clod diameter was negative ($r = -0.350$). Another indication of the preservation of these inverse relations was the negative correlation coefficient (r) between the degree of soil crumbling, K_c , and the mean clod diameter, d_c ($r = -0.332$), confirming that more intensive crumbling directly reduces the size of soil aggregates.

Among the indicators assessing losses in the main crop (C_{ur} and C_{ibr}), a positive correlation ($r = 0.356$) was observed, indicating that a proportional increase in the number of damaged and buried plants accompanied an increase in the number of cut wheat plants.

A similar positive correlation was observed between the degree of soil crumbling (K_c) and the crop injury rate (C_{ibr} ; $r = 0.307$). Such a system of dependencies illustrates the classic compromise in mechanical control. The more aggressive impact of the working section results in a wider, transverse ejection of highly fragmented soil, which, at high

speeds, breaks the shields' physical barriers and buries the main crop [34]. Summarising the results of the correlation coefficient matrix, it can be concluded that, according to the descriptive nomenclature [21], these correlations were average but statistically significant. In other cases, the correlation coefficients were not statistically significant, indicating that most indicators of the row cultivator's quality remained independent.

Table 3. Analysis of variance of speed and working depth affecting the value of the degree of soil crumbling (K_c), mean clod diameter (d_c), weed control efficiency (W_{ce}), inter-row weed removal efficiency (W_{ire}), crop uprooting rate (C_{ur}), crop injury rate (C_{ibr}).

Source of Volatility	Sum of Squares	Number of Degrees of Freedom	Medium Square	Stat F Value	p-Value
Degree of soil crumbling, K_c					
Speed: v	100.49	2	50.25	5.35	0.0065
Depth: d	24.56	1	24.56	2.61	0.1096
Interaction $v \times d$	19.01	2	9.51	1.01	0.3678
Error	788.85	84	9.39		
Mean clod diameter, d_c					
Speed: v	2.91	2	1.45	6.03	0.0036
Depth: d	0.34	1	0.34	1.39	0.2418
Interaction $v \times d$	0.08	2	0.04	0.17	0.8401
Error	20.28	84	0.24		
Weed control efficiency, W_{ce}					
Speed: v	1238.27	2	619.13	2.10	0.1292
Depth: d	3516.94	1	3516.94	11.91	0.0009
Interaction $v \times d$	1683.07	2	841.54	2.85	0.0634
Error	24,797.22	84	295.21		
Inter-row weed removal efficiency, W_{ire}					
Speed: v	251.24	2	125.62	0.34	0.7100
Depth: d	5165.27	1	5165.27	14.14	0.0003
Interaction $v \times d$	1564.94	2	782.47	2.14	0.1238
Error	30,686.87	84	365.32		
Crop uprooting rate, C_{ur}					
Speed: v	4.29	2	2.15	0.17	0.8407
Depth: d	15.42	1	15.42	1.25	0.2668
Interaction $v \times d$	6.80	2	3.40	0.28	0.7599
Error	1036.59	84	12.34		
Crop injury rate, C_{ibr}					
Speed: v	9137.86	2	4568.93	28.17	<0.0001
Depth: d	42.75	1	42.75	0.26	0.6090
Interaction $v \times d$	1108.30	2	554.15	3.42	0.0375
Error	13,624.38	84	162.20		

Post hoc analysis showed that for movement speeds of 6 and 9 km·h^{−1}, the qualitative indicators K_c , d_c , and C_{ibr} formed homogeneous groups, as indicated by Tukey's test, which showed no statistically significant differences in their mean values (Table 4).

Table 4. Mean values and $\pm$ standard deviations of row cultivator quality indicators: degree of soil crumbling (K_c), mean clod diameter (d_c), weed control efficiency (W_{ce}), inter-row weed removal efficiency (W_{ire}), crop uprooting rate (C_{ur}), crop injury rate (C_{ibr}) for three speeds of movement (v) and two working depths (d).

Factor	Level	K_c , %	d_c , mm	W_{ce} , %	W_{ire} , %	C_{ur} , %	C_{ibr} , %
v , km·h ^{−1}	6	91.27 ^{a*} $\pm$ 3.30	4.38 ^b $\pm$ 0.46	48.51 ^a $\pm$ 18.45	90.27 ^a $\pm$ 16.28	0.72 ^a $\pm$ 1.97	3.06 ^a $\pm$ 7.10
	9	91.58 ^a $\pm$ 3.16	4.11 ^{ab} $\pm$ 0.52	50.10 ^a $\pm$ 18.12	85.12 ^a $\pm$ 24.05	1.11 ^a $\pm$ 5.03	7.62 ^a $\pm$ 11.28
	12	93.78 ^b $\pm$ 2.76	3.92 ^a $\pm$ 0.47	57.02 ^a $\pm$ 19.56	88.63 ^a $\pm$ 20.95	1.30 ^a $\pm$ 2.31	26.84 ^b $\pm$ 18.9
d , mm	30	92.66 ^a $\pm$ 2.60	4.07 ^a $\pm$ 0.60	45.34 ^a $\pm$ 19.39	80.23 ^a $\pm$ 25.20	1.48 ^a $\pm$ 4.57	13.03 ^a $\pm$ 15.51
	50	91.59 ^a $\pm$ 3.76	4.21 ^a $\pm$ 0.40	58.23 ^b $\pm$ 15.87	95.90 ^b $\pm$ 9.57	0.58 ^a $\pm$ 1.59	10.65 ^a $\pm$ 17.28

* Within each factor, means followed by different lowercase letters differ significantly according to Tukey's HSD test at $p \leq 0.05$. Means sharing at least one letter belong to the same homogeneous group.

It follows that the working system of the cultivator remains stable in this range of movement speed. Only the increase in the speed of movement to 12 km·h^{−1} caused a statistically significant difference in parameters in relation to the homogeneous group, unambiguously determining the technological barrier to the usefulness of the cultivator. The analysis of the results summarised in Table 4 also allows us to notice that the transition to a greater working depth (from 30 to 50 mm) brought a highly desirable, statistically significant effect on the effectiveness of weed destruction (W_{ce} increased from 45.34% to 58.23%, and W_{ire} from 80.23% to 95.90%), without a statistically significant deterioration in plant damage rates. This is a key optimisation guideline for this type of design solution, demonstrating that depth, not speed, is the safest factor in improving weed control efficiency.

3.3. Degree of Soil Crumbling

Examples of crumbling and clodding effects after weeding under different technical parameters are shown in Figure 4. In addition to the classical parametric analysis, the variability of the cultivator's work quality indicators is graphically illustrated on box-and-whisker plots (Figure 5), which allow for the assessment of the actual distribution of data around the median and the identification of outliers and extremes. Figure 5 presents median, extreme, and outlier values, with quartiles marked; the notation is explained in the legend. For the degree of soil crumbling (K_c) and the diameter of the remaining clods (d_c), a strong concentration of results around the central values was observed, indicating high repeatability in soil loosening the inter-rows.

The increase in the working speed from 6 to 12 km·h^{−1} resulted in a slight upward shift in the interquartile interval and an increase in the median K_c index (oscillating between 91–94%), as well as a decrease in the median diameter of clods d_c (less than 4.5 mm), regardless of the depth used (Figure 5a,b). The average values of the indicators (Table 4) indicate that, as working speed increases, soil crumbling intensity increases regardless of working depth. This is more evident at a working depth of 50 mm, where a change in speed from 6 to 12 km·h^{−1} increased the crumbling rate by 3%. In addition, the increase in working speed led to more intensive soil crumbling, resulting in a reduction in the average dimension of the remaining clods in the field.

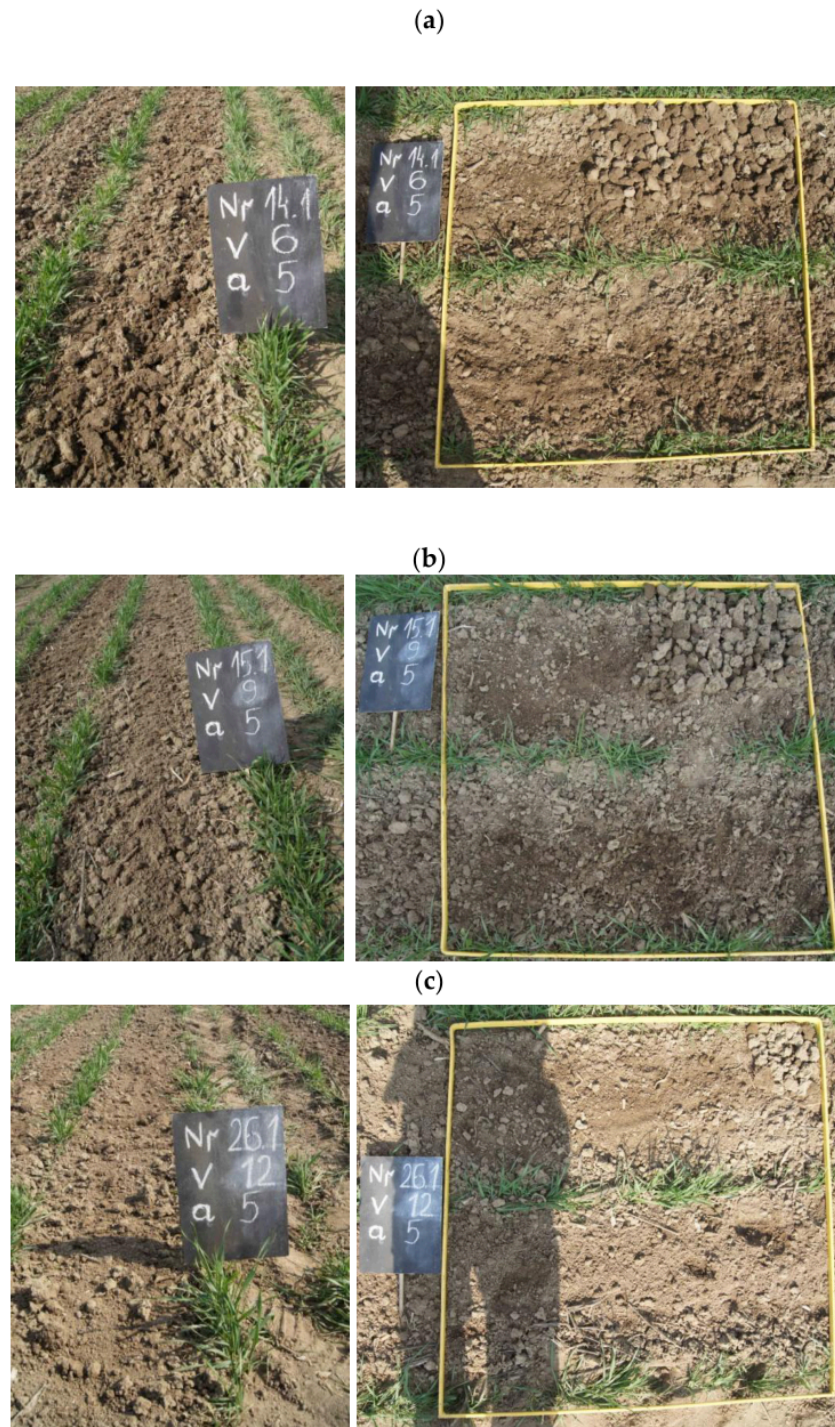


Figure 4. View of the degree of soil crumbling for the working depth of 50 mm and for the speed of movement: (a) $6 \text{ km} \cdot \text{h}^{-1}$, (b) $9 \text{ km} \cdot \text{h}^{-1}$, (c) $12 \text{ km} \cdot \text{h}^{-1}$ (on the left, photos immediately after the treatment; on the right—after selecting clods with a size of more than 30 mm).

Therefore, increasing working speed is important not only to improve treatment efficiency but also to enhance soil crumbling. On the other hand, with a smaller working depth (30 mm), the clods remaining after the cultivator had passed in the field were of a smaller diameter. This is logical, because even if under the influence of duckfoot pressure on a layer of soil with a thickness of 30 mm, the probability of formation of clods with a diameter of more than 30 mm was much lower than when working the tool at a depth of 50 mm. Therefore, the crumbling of the 30 mm-thick soil layer was more intense, resulting in smaller clods.

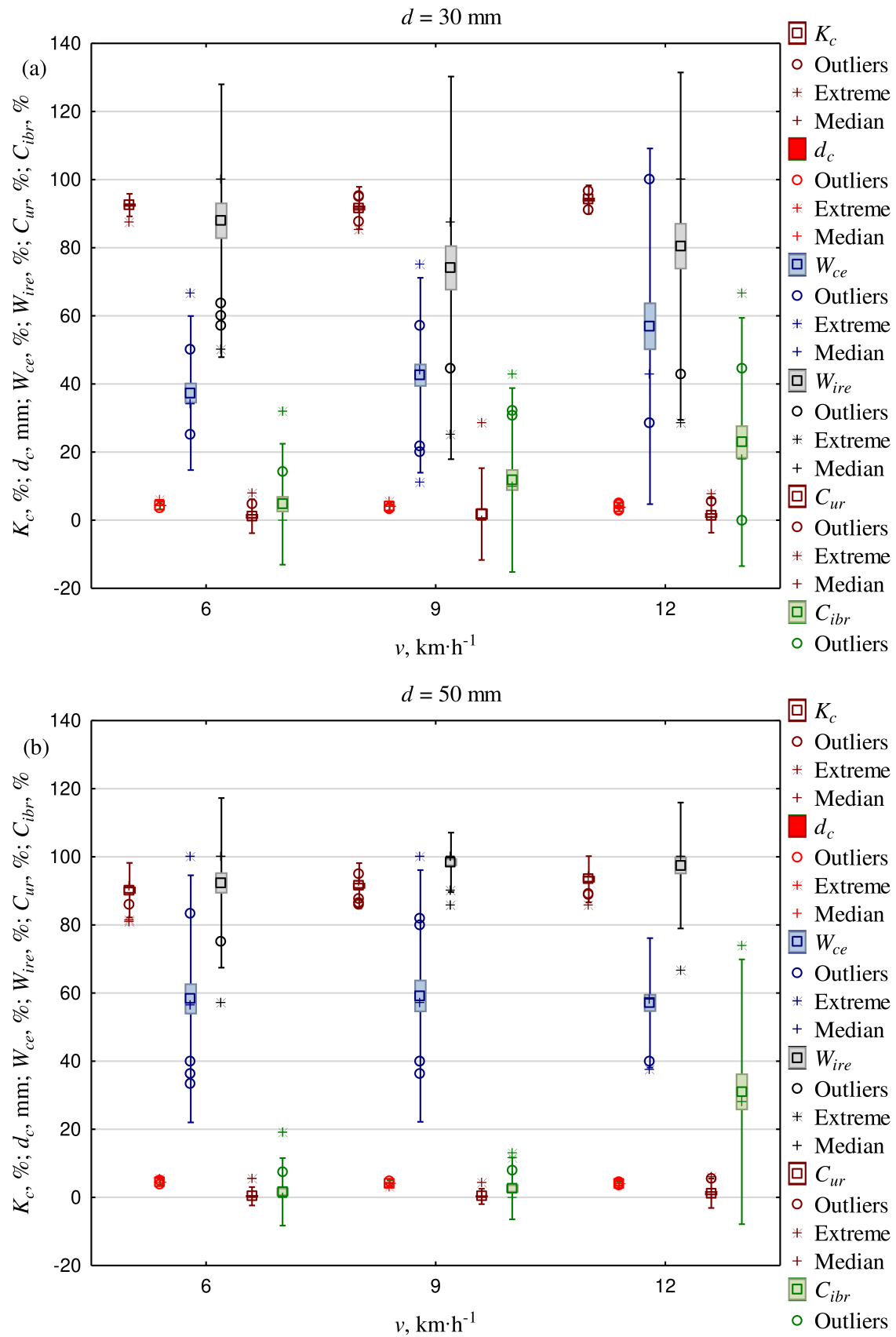


Figure 5. Box-and-whisker plots of degree of soil crumbling (K_c), mean clod diameter (d_c), weed control efficiency (W_{ce}), inter-row weed removal efficiency (W_{ire}), crop uprooting rate (C_{ur}), crop injury rate (C_{ibr}) for three movement speeds (v) 6, 9 and 12 $\text{km}\cdot\text{h}^{-1}$ and working depth (d): (a) 30 mm, (b) 50 mm.

The experimental results fully justify the conclusion that there are no grounds to reject the first hypothesis (H1), and the laws of mechanics of fragmented media strongly support the mechanism underlying the observed processes. Higher tool movement speed, particularly with the duckfoot tool type, generated much higher kinetic energy transferred to soil particles, which more effectively overcame cohesion forces, led to the cracking of internal aggregate structures, and favoured the formation of smaller soil clods [35]. This is reflected in numerical studies using the discrete element method (DEM), which show that the draught force and energy available in the strain zone increase nonlinearly with the tool dynamics [34,35]. The lack of a significant effect of working depth on the displacements of the median dimensions of the clods is probably because the dominant crumbling process was mainly initiated at the cutting edge and at the junction of the top surface of the tool, rather than by the total volume of the soil wedge being moved [11].

In the box-and-whisker plots for the degree of soil crumbling (K_c) and the diameter of the clods (d_c), single points lying outside the whisker length range (i.e., the so-called outliers and extreme values) were noted. The presence of asymmetrically distributed atypical values is characteristic of field tests, where the heterogeneity of the soil structure (its mosaicism) and local fluctuations in moisture and soil penetration resistance within the dressed paths lead to jumps in resistance, resulting in random, worse-or-better fragmentation [36]. Nevertheless, the dense cluster of quarter-stretch marks (short “boxes”) proves that the vibrating sections on the resilient tines of duckfoots showed a very high tolerance to resistance variability, maintaining, in most trials, the homogeneous grain size of soil clods desired in plant cultivation.

3.4. Weed Control Efficiency

A comparison of the mean values (Table 4) and the distributions in the box-and-whisker plots (Figure 5) clearly indicates that the key factor determining the effectiveness of weed elimination was the working depth of the tools. The increase in depth from 30 to 50 mm resulted in a clear upward trend for both analysed weed control indicators. Average weed control efficiency over the entire area (W_{ce}) increased from 45.34% to 58.23%. In comparison, the inter-row weed removal efficiency directly in the tool strip (W_{ire}) increased significantly from 80.23% to 95.90% (Table 4). Working at a depth of 50 mm enabled the cultivator to achieve a weed-removal efficiency exceeding 95%. In mechanical weed management, achieving such a high level of control without herbicides is considered optimal and highly competitive with chemical methods [3]. The analysis of variance confirmed the statistical significance of these differences ($p < 0.0001$ for W_{ire}). On the other hand, the speed of movement (v) showed only a slight, statistically insignificant trend towards an increase in the overall W_{ce} (from 48.51% at 6 km·h^{−1} to 57.02% at 12 km·h^{−1}), without affecting the inter-row weed removal efficiency of W_{ire} . This phenomenon can be explained by the varied kinematics of individual soil particles as they move around the duckfoot's wings [37]. These observations demonstrate the asymmetric effect of operating parameters on the procedure's quality, further supporting H1. The greater soil fragmentation observed at higher speeds did not necessarily result in greater weed-control effectiveness. Weed control depended primarily on the working depth, which determined whether the duckfoot sweeps effectively passed beneath the weed root zone. At 12 km·h^{−1}, the additional soil fragmentation was accompanied by greater lateral soil displacement and implement instability, increasing crop burial and mechanical injury without a corresponding improvement in weed control.

The strong dependence of weed removal effectiveness on working depth is well documented in the literature on mechanical weed control. As research shows [37,38], tools that operate too shallowly (e.g., 30 mm) often deform only the top layer of the soil,

bypassing deeper-rooted weeds or causing them to bend without permanently damaging the conductive bundles and the root system (the so-called combing effect). Only a 50 mm recess of the duckfoot tool allows for some undercutting of the root zone of most emerging weeds. In addition, the tool's deeper operation results in the formation of a larger, inverted soil wedge in front of the duckfoot tip. As demonstrated in mathematical models of soil-tool interactions [34], a larger volume of the displaced soil flow significantly affects the second key mechanism of weeding—weed burial. The flow of loosened soil effectively covers the weeds between the rows, which explains the noticeable increase in the W_{ce} index at a depth of 50 mm. The tool, which works only 30 mm deep, undercuts the shallowest root systems but does not generate enough loosened soil to bury the weeds in the row strip.

Although working at a depth of 50 mm maximises immediate mechanical weed destruction, in agricultural practice, digging deeper into the soil layer may affect the extraction of new weed seeds. Therefore, a depth of 50 mm should be considered the optimal functional solution for this particular implement, not a universal rule.

3.5. Condition of Crops

The assessment of crop condition after the cultivator's passage showed a clear distinction between two types of losses: direct plant cutting and damage, and soil covering. As indicated earlier in the statistical analysis, the crop uprooting rate (C_{ur}) did not differ significantly with movement speed or working depth, and its average remained low, at no more than 1.5%. This means that, in most cases, the geometry of the working sections and the adopted protective strip effectively limited direct contact between the duckfoot and the row of plants. In practice, this can be interpreted as evidence of the correct selection of the cultivator's basic working system under nominal conditions, when the unit's driving path remained relatively stable.

Significantly different results were obtained for the crop injury rate (C_{ibr}), which proved to be the most sensitive indicator of the cultivator's work quality. Along with movement speed, a strong upward trend in this indicator was observed. When the movement speed is increased from 6 to 9 km·h⁻¹, C_{ibr} increased from 3.06% to 7.62%, but at a speed of 12 km·h⁻¹ it reached a value of 26.84%, which should be considered an extremely unfavourable level from the point of view of the preservation of wheat crops. The literature reports that at a speed of 7.92 km·h⁻¹, excessive plant damage was observed [16]. Of the movement speeds of 3.52, 6.11, and 7.82 km·h⁻¹ used, only the latter was rated well for crop protection [13]. At higher speeds, especially at the highest speed (7.82 km·h⁻¹), inter-row cultivation with a tine cultivator was ineffective at removing weeds, resulting in significant increases in crop damage and soil coverage. Similarly, the duckfoot row cultivator would dump soil onto the crop row, increasing burial and crop damage due to its rear blade design [18].

The interpretation of the upper speed limit was based on the multiple-comparison results rather than on numerical trends alone. As shown by the Tukey HSD homogeneous groups in Table 4, the 12 km·h⁻¹ level differed significantly from the lower speed levels for the immediate crop injury indicator. In contrast, the corresponding increase in speed did not provide a statistically significant improvement in weed-control effectiveness. Therefore, under the tested field conditions, the 12 km·h⁻¹ treatment represented a less favourable operating level because it increased immediate crop injury without a commensurate statistically supported benefit in weed control.

The increase in immediate crop injury at 12 km·h⁻¹ may have resulted from several interacting mechanisms. These include increased lateral soil discharge, higher dynamic excitation of the implement sections, and possible short-term fluctuations in the realised working depth. The independent sections with copying wheels and articulated parallelo-

grams were designed to maintain the preset depth, but continuous depth measurements were not collected during the field passes. Consequently, the present data demonstrate an association between high operating speed and crop injury but do not allow the individual contribution of depth fluctuation, vibration, and lateral soil throw to be separated.

This interpretation is consistent with our soil-bin studies, in which duckfoot tools were tested at different operating speeds and working depths, and the geometry of the resulting furrows was measured [38]. Those experiments showed that speed and depth affect the cross-sectional characteristics of the disturbed soil and furrow profile. However, soil-bin results cannot be transferred directly to field conditions because they do not reproduce the spatial heterogeneity of the field, crop rows, or operator-guidance effects. Direct field measurements using continuous depth and frame-motion sensors are therefore needed to quantify the dynamic response of the working sections.

In addition, the previous analysis of variance showed the statistical significance of both the influence of speed itself and the interaction of speed with working depth, which confirms that the deterioration of the plant condition was not the result of a simple, uni-factorial interaction but resulted from a more complex coupling of the parameters of the tool's movement with the dynamics of soil movement. The experimental results fully support the conclusion that there are no grounds to reject the second hypothesis (H2). The sentence, assuming that after exceeding the critical working speed (here $9 \text{ km} \cdot \text{h}^{-1}$), there is a sharp increase in the backfilling of crops and the explanation that this is due to the excessive dynamics of lateral ejection of soil by the wings of duckfoots and the vibration of the sections that overcome the discs covering the crops, was logically formulated.

The increase in working speed not only increased the energy transferred to the clods and soil particles but also altered their trajectories after leaving the cutting zone. Numerical studies of DEM and FEM have shown that with increasing speed of movement of flat duckfoot tools, not only does the draught force increase, but also the intensity of lateral ejection of the displaced soil and the tendency to form a dynamically deformed soil wedge in front of the working part of the tool. In field conditions, this means that at higher speeds, the soil mass moved through the extreme working sections gains more momentum, and its flow can bypass or partially exceed the side covers. For this reason, crops located near the protective strip are destroyed not only directly by the blade but also indirectly by impact and by backfilling with soil. This mechanism explains well why C_{ur} remained low, while C_{ibr} increased rapidly with speed.

The influence of dynamic vibrations of the entire working system cannot be overlooked either. At high travel speeds, the amplitude of the transverse swings of the frame and working sections increases, especially when the machine is operating in a field with a heterogeneous physical structure and locally variable conciseness. Under such conditions, the nominal 75 mm protective strip ceases to be geometrically constant, as the actual trajectory of the shields and duckfoots is temporarily deviated. Studies on weeding tool modelling indicate that even small changes in soil contact conditions and resistance can cause local disturbances in movement stability, changes in stress distribution, and alterations in particle trajectories [39]. Therefore, the protective zone of the row is periodically violated, increasing the likelihood of mechanical damage to leaves, crop bending, and partial or complete burial.

In practical terms, these results indicate that the risk of direct plant cutting did not determine the limit of safe use of the tested cultivar, but rather the increasing effects of secondary impacts from the soil flow. This is important for designing modern row cultivators because the correct positioning of the working tools alone does not guarantee protection of the main crop. Equally important is the system's ability to dampen vibrations, stabilise the driving path, and control lateral soil flow. In this context, the results obtained support

the development of structures equipped with active guidance systems, vision sensors, and more effective row-zone covers, as only such solutions can reduce the discrepancy between high weed-control efficiency and crop safety [40].

From a scientific point of view, it is particularly important that the analysis of crop conditions most fully reveals the limitations of simply increasing treatment intensity. The increase in speed improved selected indicators of soil impact, but it also triggered secondary mechanisms that led to unacceptable biological losses. This means that the optimisation of the cultivator's work must not be based solely on maximising weed destruction or soil crumbling but must also consider a multi-criteria balance between agrotechnical effect and crop protection. This is where field studies prove irreplaceable, as they are the only ones that allow us to capture the real coupling between tool movement, soil flow, and the response of living plants, which cannot be fully reproduced in either laboratory experiments or simplified numerical models.

Immediate crop injury should be distinguished from irreversible yield loss. Plants that are bent or partially covered with soil may recover, depending on the duration of burial, the degree of tissue damage, crop developmental stage, subsequent weather conditions, and competition from surviving weeds. In contrast, plants that are completely cut or uprooted are more likely to represent irreversible losses. However, the present experiment did not include follow-up observations of plant recovery, biomass accumulation, or final yield. Consequently, the measured injury rate cannot be converted directly into yield loss or economic loss. Quantifying these effects would require a separate longitudinal field experiment with post-treatment assessments and appropriate yield-related controls, such as untreated and alternative weed-control treatments.

4. Conclusions

Based on the research conducted, the working parameters of the cultivator have an asymmetric effect on the machine's operational quality. Increasing movement speed from 6 to 12 km·h⁻¹ increased soil crumbling and reduced the mean clod diameter. At the same time, the effectiveness of weed destruction depended primarily on the depth of tool operation. Working duckfoots at a depth of 30 mm did not achieve the required weeding efficiency, whereas a depth of up to 50 mm exceeded the 95% effectiveness threshold.

Based on the Tukey HSD comparisons of the tested treatment means, operating speeds below 12 km·h⁻¹, particularly the nominal 9 km·h⁻¹ level, provided the most favourable balance between weed-control effectiveness and immediate crop injury under the conditions of this field experiment. This conclusion is consistent with recommendations regarding an optimal weeding speed of 8–9 km·h⁻¹ for inter-row cultivators [13,16]. This range should not be interpreted as a generally optimised speed, as no formal optimisation procedure was applied. It represents a practical balance between weed-control effectiveness, soil fragmentation, and immediate crop injury under the conditions of the present field experiment. After exceeding the speed of 9 km·h⁻¹, there was no clear improvement in other indicators of work quality, but damage and overburdening of crops increased sharply. This means that any further increase in speed no longer provides agrotechnical benefits but only worsens the safety of the main crop. The reported crop injury rate refers to visible injury recorded immediately after treatment, including cutting, bending, breaking, and soil burial. It should not be interpreted as irreversible crop loss or yield reduction because subsequent plant recovery and final yield were not assessed.

The most advantageous compromise between treatment effectiveness and crop protection was a depth of 50 mm and a speed of no more than 9 km·h⁻¹. The results therefore confirm the need to select work parameters not only to maximise weeding, but also to reduce crop losses. In further studies, it would be useful to extend the analyses to different

soil conditions and weed and crop development phases, and to evaluate solutions that improve track stability and reduce lateral soil ejection.

The applicability of these results is subject to experimental conditions, including the banded wide-row wheat arrangement, the developmental stage and composition of the weed community, and the measured soil moisture, bulk density, and penetration resistance. Different soil textures, moisture conditions, soil structures, crop stages, or weed communities may alter soil-tool interactions, thereby changing both weed-control effectiveness and the risk of crop injury. The operating range identified here should consequently be regarded as condition-specific rather than universally transferable. Multi-site and multi-season experiments are needed to assess the stability of these relationships under a broader range of soil and crop conditions.

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