V International Scientific and Technical Conference Actual Issues of Power Supply Systems

Multifactor Experimental Optimization of Disc Arrangement Parameters and Operating Speed of a Two-Tier Disc Plough

AIPCP25-CF-ICAIPSS2025-00458 | Article

Multifactor Experimental Optimization of Disc Arrangement Parameters and Operating Speed of a Two-Tier Disc Plough

Takhirjan Pulatov[1], Ramzjon Hamroev[2, a)], Rustamjon Abdumajidov[2], Timur Beketov[2]

[1] Turin Polytechnic university in Tashkent, Tashkent, Uzbekistan
[2] Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan

[a)] Corresponding author: hamroyevr@mail.ru

Abstract. The performance of two-tier disc ploughs largely depends on the geometric arrangement of disc working bodies and the operating speed of the tillage aggregate. This study presents a multifactor experimental optimization of the geometric parameters and operating speed of a two-tier disc plough aimed at improving plant residue incorporation while minimizing total draft resistance. A four-factor experimental design based on the Hartley-4 plan with half replication was applied. The investigated factors included the transverse offset of the upper-tier disc working body, the longitudinal distances between the upper- and lower-tier disc bodies, and the forward speed of the tillage aggregate. Regression analysis revealed a nonlinear interaction between the investigated parameters. The results showed that increasing the transverse offset and longitudinal spacing between disc bodies improves residue incorporation only up to a certain limit, after which soil flow continuity is disturbed and efficiency decreases. Optimization using the penalty function method indicated that stable incorporation of plant residues to a depth of 18–22 cm with minimal draft resistance is achieved when the transverse offset is 17–28 cm, the longitudinal distances are 47–53 cm and 54–56 cm, and the operating speed is 6.5–9.5 km/h. The obtained results provide a practical basis for improving the agro-technical performance and energy efficiency of two-tier disc ploughs under field conditions.

INTRODUCTION

The performance of two-tier disc ploughs is largely governed by the geometric arrangement of the upper- and lower-tier disc working bodies and by the operating speed of the tillage aggregate. In practical field conditions, inappropriate transverse and longitudinal spacing between disc bodies disrupts the soil flow pattern, resulting in incomplete incorporation of plant residues, non-uniform working depth, and a substantial increase in total draft resistance. Owing to the specific cutting–lifting and partial inversion mechanism inherent to disc working bodies, the mutual positioning of the upper and lower tiers plays a decisive role in determining both agro-technical performance and energy efficiency [1,2,].

Most existing studies on disc plough design focus on individual geometric parameters, such as disc angle, disc diameter, or working depth, or examine operating regimes independently. Such an approach does not allow reliable identification of rational combinations of geometric parameters and operating conditions that simultaneously ensure effective incorporation of plant residues and acceptable energy consumption under real field conditions. This limitation is particularly pronounced for two-tier disc ploughs, where complex interactions between the upper and lower disc bodies govern soil fragmentation, residue displacement, and traction resistance [3,4].

In this study, the optimal combination of geometric parameters and operating conditions of a two-tier disc plough is determined using a multifactor experimental approach. A four-factor experimental design based on the Hartley-4 (Ha4) plan with half replication was employed to evaluate the influence of the transverse offset of the upper-tier disc body relative to the lower-tier disc body, the longitudinal distances between the upper and lower disc bodies, and the forward speed of the tillage aggregate. The depth of plant residue incorporation and the total draft resistance of the disc plough were selected as the main performance criteria, allowing a simultaneous assessment of tillage quality and energy demand. The obtained results provide experimentally substantiated parameter ranges that ensure effective incorporation of plant residues at the required depth while minimizing draft resistance, thereby improving the operational efficiency of two-tier disc ploughs [5,6,7,8].

MATERIALS AND METHODS

A four-factor experimental study was conducted to determine rational geometric parameters and operating modes of a two-tier disc plough using a Hartley-4 (Ha4) experimental design with a half-replication scheme. The investigated factors were as follows: the transverse offset of the upper-tier disc working body relative to the lower-tier disc body (X_1 = 0–30 cm), the longitudinal distance between the upper-tier disc body and the preceding lower-tier disc body (X_2 = 45–65 cm), the longitudinal distance between the lower-tier disc body and the preceding upper-tier disc body (X_3 = 35–55 cm), and the forward speed of the tillage aggregate (X_4 = 6.0–9.0 km/h). The selected variation ranges were established based on preliminary theoretical considerations and single-factor experimental studies to ensure that the optimal parameter values lay within the experimental domain and that all combinations of the experimental matrix could be practically implemented [9,10,11].

The depth of plant residue incorporation and the total draft resistance of the disc plough were selected as the response variables. Regression models were derived from the experimental data, and the homogeneity of variances and adequacy of the models were verified using the Cochran and Fisher criteria, respectively. Optimization of the geometric parameters was performed using the penalty function method at three discrete levels of forward speed (6.0, 7.5, and 9.0 km/h) to identify parameter combinations that ensured effective incorporation of plant residues to a depth of at least 15–22 cm while maintaining minimal draft resistance. This depth range reflects the technological characteristics of disc working bodies, which provide cutting, lifting, and partial inversion of the soil layer rather than complete inversion.

Field experiments were carried out using a prototype two-tier disc plough equipped with adjustable upper- and lower-tier disc bodies, allowing independent variation of transverse and longitudinal geometric parameters within the specified ranges. The disc plough was aggregated with an agricultural tractor, and draft resistance was measured using a dynamometric system installed between the tractor and the plough frame, enabling continuous recording of traction forces under steady-state operating conditions. The working depth was controlled mechanically and maintained constant throughout the experiments, with deviations not exceeding ±5%. Each experimental run was conducted on a test plot of sufficient length to ensure stabilization of traction forces and to exclude transient operating regimes.

The depth of plant residue incorporation was determined by direct measurements performed in soil cross-sections perpendicular to the direction of travel. After tillage, soil layers were carefully excavated at fixed intervals, and the vertical position of incorporated plant residues was measured relative to the soil surface. For each experimental condition, multiple measurements were obtained and averaged to reduce random error. The experimental data were processed using second-order regression equations derived from the Hartley-4 experimental matrix. Statistical reliability of the models was assessed by evaluating variance homogeneity using the Cochran criterion and model adequacy using the Fisher criterion, ensuring the validity of the derived relationships and their applicability for optimizing the geometric and operating parameters of the two-tier disc plough [12,13,14].

RESULTS AND DISCUSSION

To interpret the experimental results and to justify the rational values of the geometric parameters of the two-tier disc plough, a geometrical analysis of the transverse displacement of soil flow generated by the upper-tier disc working bodies was performed. The analysis is based on the schematic representation shown in Fig. 2.6, which illustrates the interaction between the soil slice cut by the upper-tier disc body and the furrow formed by the lower-tier disc body.

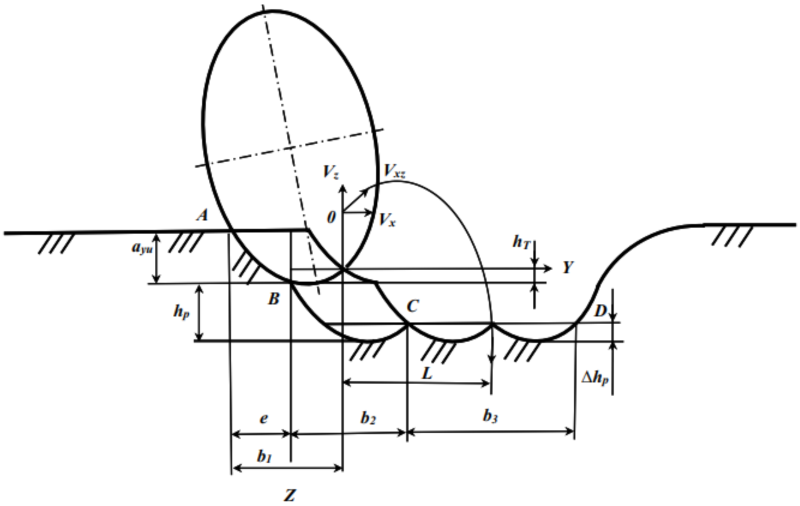

Fig. 2. Schematic representation of the transverse displacement of the upper-tier disc working body relative to the lower-tier disc working body

For effective and stable incorporation of plant residues, weed biomass, and seeds into the soil layer, the soil slice detached by the upper-tier disc working body must be displaced transversely and deposited into the furrow formed by the preceding lower-tier disc body. This condition ensures that the soil material released from the upper tier is fully covered by the soil flow generated by the lower tier, preventing residue accumulation on the soil surface and minimizing secondary redistribution.

Based on the geometric relationships shown in Fig. 1, the required transverse displacement e of the upper-tier disc working body relative to the lower-tier disc body can be expressed as:

$$e = b_1 + L - b2 - 0{,}5b_3, \quad (1)$$

where b_1 is the transverse distance between points A and O defining the width of the furrow bottom formed by the upper-tier disc body, L is the transverse displacement distance of the soil slice released from the upper-tier disc body, b_2 is the transverse distance between points B and C, and b_3 is the transverse distance between points C and D, as indicated in Fig. 1.

The transverse distance b_1 is determined from the geometric relationship between the disc penetration depth and the installation angles of the disc working body and is given by:

$$b_1 = \left[\sqrt{\frac{h_{yu}}{\cos\beta}\left(D - \frac{h_{yu}}{\cos\beta}\right)} + \sqrt{\frac{h_T}{\cos\beta}\left(D - \frac{h_T}{\cos\beta}\right)} \right] \sin\alpha; \quad (2)$$

where D is the disc diameter, α is the disc installation angle relative to the direction of travel, β is the disc inclination angle relative to the vertical plane, h_T is the vertical distance from the soil surface to the position where the soil slice released from the upper-tier disc body enters the furrow, and Δh_p characterizes the height of longitudinal surface irregularities formed by the lower-tier disc bodies.

This geometrical analysis confirms that the transverse offset between the upper- and lower-tier disc working bodies plays a decisive role in controlling the trajectory of the soil flow and the final position of incorporated plant residues. Therefore, the transverse offset parameter eee was selected as one of the key factors in the multifactor experimental study, and its influence on residue incorporation depth and total draft resistance was further evaluated using regression analysis and constrained optimization.

The results of the multifactor experimental study and data processing carried out using the PLANEXP-2 software are presented in Appendices 1 and 2. The experimental domain was defined by the factor levels and variation ranges summarized in Table 1, which specifies the investigated factors, their coded designations, measurement units, variation intervals, and levels (−1, 0, +1). This experimental domain ensured the feasibility of all combinations of the experimental matrix and enabled reliable identification of the influence of geometric parameters of the upper- and lower-tier disc working bodies, as well as the operating speed of the tillage aggregate, on the response variables characterizing the performance of the two-tier disc plough.

TABLE 1. Factor levels and variation intervals

Factors	Unit	Coded designation of factors	Variation interval	Factor levels		
				Lower (−1)	Base (0)	Upper (+1)
1. Transverse offset of the upper-tier disc working body relative to the lower-tier disc body	cm	X_1	15	0	15	30
2. Longitudinal distance between the upper-tier disc working body and the preceding lower-tier disc body	cm	X_2	10	45	55	65
3. Longitudinal distance between the lower-tier disc body and the preceding upper-tier disc working body	cm	X_3	10	35	45	55
4. Forward speed of the tillage aggregate	km/h	X_4	1.5	6.0	7.5	9.0

Processing of the experimental data resulted in the derivation of regression equations that adequately describe the investigated process with respect to the selected evaluation criteria. The dependence of the total draft resistance of the two-tier disc plough (kN) on the investigated factors is described by Eq. (1):

$$У_p = 11{,}450 + 0{,}068\,X_1 - 0{,}080\,X_2 - 0{,}749\,X_3 + 0{,}728\,X_4 - 0{,}440X_1^2 - 0{,}308X_2^2 + 0{,}470\,X_2\,X_3 + 0{,}488X_3^2 + 0{,}085\,X_3\,X_4 + 0{,}883X_4^2 \quad (3)$$

The dependence of the depth of plant residue incorporation (cm) on the same factors is described by Eq. (2):

$$У_p = 24{,}703 + 0{,}941\,X_1 + 0{,}995\,X_2 - 2{,}478\,X_3 + 2{,}128\,X_4 - 4{,}701X_1^2 - 0{,}345\,X_1\,X_2 + 0{,}232\,X_1\,X_4 - 3{,}107X_2^2 - 2{,}946\,X_2\,X_3 - 1{,}241\,X_2\,X_4 - 2{,}534X_3^2 - 0{,}582\,X_3\,X_4 + 1{,}366X_4^2 \quad (4)$$

Analysis of Eqs. (3) and (4) shows that the total draft resistance of the two-tier disc plough and the depth of plant residue incorporation are governed by a nonlinear interaction of the investigated geometric parameters and operating speed. Within the experimental domain defined in Table 1, an increase in the transverse offset of the upper-tier disc working body from 0 to approximately 15–20 cm, combined with an increase in the longitudinal distance between the upper-tier and the preceding lower-tier disc bodies from 45 to about 55 cm, leads to an increase in the depth of plant residue incorporation. This trend is associated with improved cutting and rolling conditions along the disc surfaces and more effective displacement of soil slices between the tiers.

However, further enlargement of these parameters results in a deterioration of the soil flow continuity between the upper and lower tiers. Under these conditions, partial accumulation of soil and plant residues occurs in front of the disc working bodies, which causes a decline in residue incorporation efficiency after reaching a local maximum. Such behavior is characteristic of disc ploughs and is related to the rolling–sliding interaction between the disc surfaces and the soil layer.

An increase in the longitudinal distance between the lower-tier disc body and the preceding upper-tier disc body from approximately 35 to 50–55 cm improves the quality of residue incorporation while simultaneously reducing total draft resistance. This effect can be explained by a more uniform redistribution of soil between the tiers and a reduction in rolling resistance acting on the lower-tier disc bodies.

The forward speed of the tillage aggregate exerts a pronounced influence on both response variables. When the operating speed increases from 6.0 to 9.0 km/h, the depth of plant residue incorporation increases due to intensified soil fragmentation and rolling action of the disc working bodies. At the same time, the total draft resistance increases as a result of higher inertial and frictional forces arising at the soil–disc interface. These results confirm the statistical significance of all investigated parameters, as reflected in Eqs. (3) and (4).

The optimal parameter values were obtained by solving the constrained optimization problem using the penalty function method, which enables simultaneous fulfillment of the required plant residue incorporation depth and minimization of total draft resistance. Based on this approach, rational combinations of the transverse offset of the upper-tier disc working body relative to the lower-tier disc body, the longitudinal distance between the upper-tier disc body and the preceding lower-tier disc body, and the longitudinal distance between the lower-tier disc body and the preceding upper-tier disc body were determined for selected operating speeds of the tillage aggregate. The resulting optimal configurations, corresponding to operating speeds in the range of 6.5–9.5 km/h, are summarized in Table 2.

TABLE 2. Optimal values of factors for a two-tier disc plough

$V\ (X_4)$, км/ч		$e\ (X_1)$, см		$l_1\ (X_2)$, см		$l_2\ (X_3)$, см	
Coded	Natural	Coded	Natural	Coded	Natural	Coded	Natural
-1	6.5	0.120	17.0	−0.380	52.0	0.920	55.0
0	8.0	0.180	18.0	−0.320	53.0	0.840	54.0
+ 1	9.5	0.820	28.0	−0.850	47.0	1.000	56.0

Analysis of the optimized results presented in Table 2 indicates that stable incorporation of plant residues into the soil layer with minimal total draft resistance is achieved within well-defined ranges of geometric parameters for the two-tier disc plough. In particular, effective residue incorporation to a depth of approximately 18–22 cm, which is characteristic of disc working bodies, is obtained when the transverse offset of the upper-tier disc working body is maintained within 17–28 cm. At the same time, the longitudinal distance between the upper-tier disc body and the preceding lower-tier disc body should be kept within 47–53 cm, while the longitudinal distance between the lower-tier disc body and the preceding upper-tier disc body should lie within 54–56 cm.

These parameter ranges remain consistent across the investigated operating speed interval of 6.5–9.5 km/h, indicating a high degree of robustness of the optimized geometric configuration with respect to changes in operating speed. The obtained ranges reflect the specific soil processing mechanism of disc working bodies, in which cutting, rolling, and redistribution of the soil layer govern both residue incorporation efficiency and energy consumption.

The established parameter ranges provide a physically and technologically justified basis for configuring the relative arrangement of the upper and lower-tier disc working bodies. Their practical implementation makes it possible to achieve the required agrotechnical performance while limiting excessive energy consumption, which is of considerable importance for the efficient operation of two-tier disc ploughs under field conditions.

CONCLUSIONS

Experimental results showed that the performance of the two-tier disc plough is strongly influenced by the geometric arrangement of the disc working bodies and operating speed. Increasing the transverse offset of the upper-tier disc body to about 15–20 cm and the longitudinal distance between the upper-tier and preceding lower-tier disc bodies to approximately 55 cm improved plant residue incorporation, while further increases led to soil flow disruption and reduced efficiency. Increasing the longitudinal distance between the lower-tier and preceding upper-tier disc bodies to 50–55 cm reduced total draft resistance. An increase in operating speed from 6.0 to 9.0 km/h enhanced residue incorporation but increased draft resistance.

Optimization results indicated that stable incorporation of plant residues to a depth of 18–22 cm with minimal draft resistance is achieved at transverse offset values of 17–28 cm, longitudinal distances of 47–53 cm and 54–56 cm between disc bodies, and operating speeds of 6.5–9.5 km/h. These ranges remained consistent across the investigated speed interval, confirming the practical applicability of the optimized configuration for two-tier disc ploughs.

REFERENCES

1. Isya Al Hanif, Sandra Malin Sutan, Wahyunanto Agung Nugroho Test of Disc Plow Implement for Soil Tillage Using John Deere Tractor Type of 6110 B with 117/2100 Hp of Power Jurnal Keteknikan Pertanian Tropis dan Biosistem Vol. 3 No. 3, Oktober 2015, 372-381

2. Shabanpour M. Fekrı S Bagherı I Payman S. H. & Rahimi ajdadi F 2022 Effects of tillage method and drainage management on some soil physical properties Journal of Agricultural Sciences Volume: 28 Issue: 3, 545 - 554, 05.09.2022

3. Sh. J. Imomov, J. U. Ruzikulov, S. S. Kurbanbayev, H. S. Safarov, K. S. Sobirov, and Z. Sh. Isakov "Technological process of provisional dig a ditch", Proc. SPIE 12296, International Conference on Remote Sensing of the Earth: Geoinformatics, Cartography, Ecology, and Agriculture (RSE 2022), 122960O (6 July 2022); https://doi.org/10.1117/12.2642980

4. Safarov J.E., Sultanova Sh.A., Gunes G., Ponasenko A.S., Ponasenko A.S., Samandarov D.I. Research of the Effective Diffusion Coefficient and Activation Energy for the Purpose of Energy Saving during Convection Drying. Aip Conference Proceedings, 3331(1), 030025, 2025. DOI: 10.1063/5.0306188

5. Lima R.P., Rolim M.M. Dantas D, Silva A, Mendonça E.A., Compressive properties and least limiting water range of plough layer and plough pan in sugarcane fields. Soil Use Manag. 2020, 37, 533–544
6. Ishmuradov S., Hamroev R. Disc rotary plough for agriculture mechanization X International Conference on Advanced Agritechnologies, Environmental Engineering and Sustainable Development AGRITECH-X 2024 E3S Web Conf. Volume 548
7. Shukurov Shahobiddin, Alikulov Adkham, Normurodov Ulugbek, Tlovoldiyev Shokhrukh, Sattarov Akmaljon, Chulliyev Zulfiqor, Khojibekova Shokhida. Liquid nitriding technology for high-speed steel milling cutters. International Journal of Mechatronics and Applied Mechanics 2025, Issue 22, Vol. II. Pp: 205-212.
8. Ishmuradov S., Abdumajidov R. Results of acceptance tests of the disk plow for tillage in agriculture // Bio Web of Conferences, 2024, 105, 01028
9. Al-Jarrah, M. Abdul Malik, Saddam H. M. and Rafi Abd al-Sattar (2006). Effect disk angle and plowing speed in some physical properties of soil and performance of vertical disk plow. Mesopotamia journal of Agriculture vol. 34 No. (2), 2006, pp. 129 – 134
10. Shinsuke Konno, Hayato Shindo, Mitsuhiko Katahira, Motoyasu Natsuga Effects of Agricultural Machine Fuel Consumption on Paddy Fields Journal of Agricultural Science and Technology B 7 (2017) 170-178
11. Tiessen K, Sancho F, Lobb D., Mehuys G Assessment of tillage translocation and erosion by the disk plow on steepland Andisols in Costa Rica. J. Soil Water Conserv. 2010, 65, 316–328.
12. Rasulov, A., Alikulov, A., Djalolova, S., Tukhtasheva, M., Fayzullayev, A., & Sattarov, A. (2024). Manufacturing tools with a combination of strength and ductility using molybdenum powders. International Journal of Mechatronics and Applied Mechanics, (18), Pp: 216-221.
13. Pulatov, T.R. Experimental Studies on Friction Processes in Sliding Thrust Bearings. Journal of Friction and Wear, 2021 | Journal article, DOI: 10.3103/S1068366621010074, EID: 2-s2.0-85102599923, Part of ISSN: 19349386 10683666.
14. A. Abdazimov, Anvar, T., Pulatov, Takhirjan, K., Odiljon, Kholikulov. Conceptual principles for developing a universal energy source for the cotton growing zone. AIP Conference Proceedings 2024. III International scientific and technical conference "actual issues of power supply systems" (ICAIPSS2023), 7–8 September 2023, Tashkent, Uzbekistan.