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Parameter Optimization And Economic-Statistical Analysis Of A Flexible Cable-Driven Rotary Harrow For High-Speed Pre-Sowing Cultivation

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Abstract

Achieving high-quality seedbed preparation in heavy clay-loam environments remains a significant challenge for conventional tillage implements. This study investigates the structural kinematics and technological optimization of a novel, patented flexible cable-driven rotary harrow. The research integrates advanced mathematical modeling of rotary tillage dynamics with empirical field validation conducted at the Ganja RAEM experimental station using a Belarus-892 tractor. The innovative design employs a discrete chain-cable synchronization system, which enhances adaptability to soil micro-relief compared to rigid-axle benchmarks. Experimental data demonstrate that the prototype maintains superior operational stability at high-speed regimes of 14–16 km/h, achieving a mean cultivation depth of 7.72 cm with a uniformity coefficient of V=14.25%. Through Response Surface Methodology (RSM), it was confirmed that the synergy between a 380 mm rotor diameter and a 15 km/h forward velocity optimizes the soil crumbling degree to a peak of 81.28%. Notably, the agronomically optimal fraction (<10 mm) reached 51%, with an experimental precision of P=2.85%. Transitioning to this flexible cable-driven system resulted in a profound resource-saving effect, reducing labor intensity by 62.3% and operational expenditures by 55.3%. With a calculated net annual economic benefit of 7,783.7 AZN per unit, the implementation ensures a rapid return on investment. This study introduces a first-of-its-kind synchronization framework for rotary soil-engaging components, providing a robust scientific basis for the next generation of high-speed, energy-efficient agricultural machinery.

Keywords: *flexible cable harrow, rotary cultivation, crumbling degree, economic efficiency, statistical analysis, pre-sowing preparation*

Introduction

Relevance of the topic. Increasing crop productivity while reducing costs in plant cultivation is a global challenge. Effective weed control, soil aeration, and nutrient management can be successfully addressed through the modernization of agricultural machinery. Scientific research indicates that after plowing, one hectare of soil contains between 100 million and 3 billion weed seeds. Approximately 70–90% of these can be eliminated before and after germination through mechanical harrowing. By reducing the reliance on expensive herbicides, harrowing mitigates chemical pressure on the soil biota and improves soil structure (Kushwaha, R. L.,et.al,1996; Məmmədov, Q. Ş.,2007; Məmmədov, N. N.,et.al,2007).

Global experience shows that using rotary harrows in wheat and other grain cultivation increases productivity by 10–15%. These tools facilitate better root aeration and create an optimal environment for seed development. Furthermore, the rotation of the harrow reduces resistance forces, thereby preventing friction-induced wear and extending the machine's operational lifespan (Aslami, M.,et.al,2022; Topakci, M.,et.al,2010).

Scientific novelty. For the first time in the Republic, a flexible rotary harrow has been designed where the traditional rigid axles of the working organs are replaced with a chain-cable system. This innovative design has been patented and tested at the invention level to suit local soil-climatic conditions.

Working hypothesis. High-quality soil loosening in grain cultivation is achieved by selecting optimal structural and technological parameters for the flexible cable harrow, depending on the physical-mechanical properties of the soil.

Materials And Methods.

Structural design of the flexible cable harrow. The research focuses on an innovative flexible rotary harrow designed to overcome the limitations of rigid-axle implements (Qurbanov,H.N. 2024; Sadiqov, M. A. 2015; Zhang, J.,et.al,2023). The machine's architecture was developed according to the Unified System for Design Documentation (USDD) (Fig.1). The primary components of the prototype include:

- **Frame and hitching system:** A reinforced chassis designed for Category 2 three-point linkage.

- **Flexible working unit:** The core innovation consists of toothed rotors interconnected via a high-strength steel cable-chain system. This assembly allows the rotors to “float” and maintain constant contact with the soil surface regardless of micro-relief irregularities.
- **Depth control mechanism:** Adjustable support wheels that regulate the penetration depth of the teeth within the required 5–10 cm range.

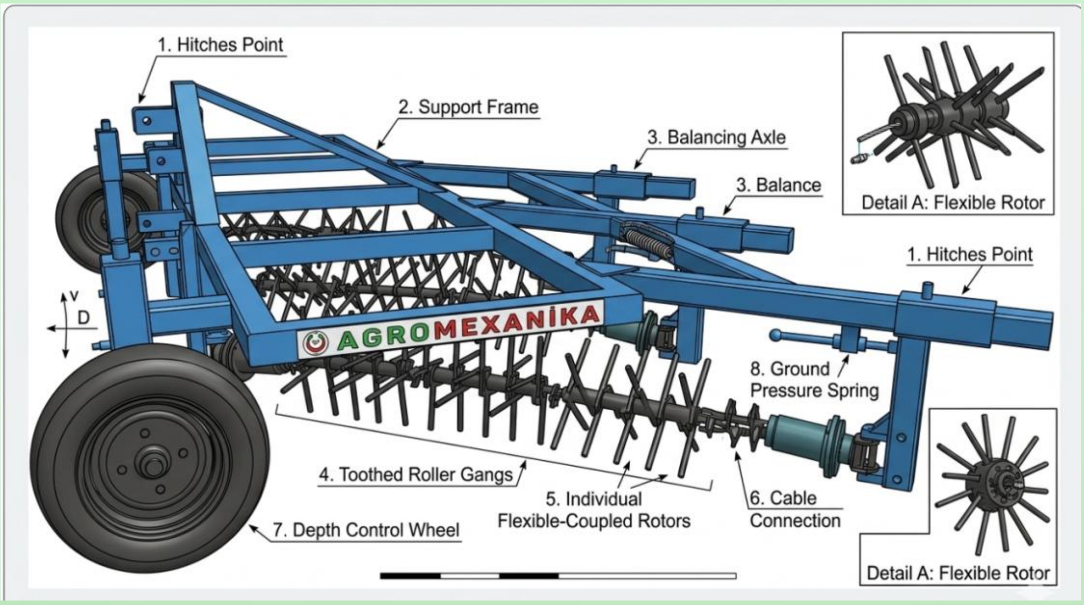

Figure 1: Schematic and detailed component breakdown of the innovative flexible cable-driven rotary harrow

Theoretical framework and design calculations. The draft resistance (P) of the aggregate was determined using the Grandvoinnet-Goryachkin theoretical model, which accounts for the energy consumed in overcoming rolling resistance and the deformation of the soil layer (Srivastava, A. K., et.al.,2006).

$P = f\ Q + k\ a\ b + \varepsilon\ a\ b\ V^2$;

Calculations were based on the prototype’s structural weight (Q = 6608 N), a rotor diameter of 380 mm, and a total working width of 3.5 meters.

Site characteristics and experimental setup. Field experiments were conducted at the Ganja Regional Agro-Service Center (RAEM) experimental base (Fig.2).

- **Traction unit:** A "Belarus-892" tractor (Class 1.4) was utilized for all trials.
- **Soil conditions:** The trials were performed on heavy clay-loam soils. The soil density was recorded at 0.986 g/cm^3 with an average moisture content of 18–24% during the testing period.

Measurement and analytical procedures. To evaluate the technological and economic performance, the following methodologies were applied:

- **Soil fraction analysis:** After the harrowing process, soil samples were collected from the 0–15 cm layer. A set of specialized sieves was used to categorize the soil particles into five fractions (<10 mm, 10–25 mm, 25–50 mm, 50–100 mm, and >100 mm).
- **Statistical data processing:** All experimental results were subjected to regression and statistical analysis using **excel**. Key metrics calculated included the arithmetic mean (X), standard deviation (σ), coefficient of variation (V), and the relative precision of the experiments (P).
- **Economic evaluation:** The cost-effectiveness was assessed by comparing the reduction in labor intensity and fuel consumption against the baseline performance of standard rigid-type rotary harrows currently used in the region.


Figure 2. Field test of a flexible cable-driven rotary harrow

Results And Discussion.

Analysis of soil fragmentation dynamics. The performance of the flexible cable-driven rotary harrow was evaluated based on its ability to pulverize heavy clay-loam soil into agronomically valuable fractions. Field experiments conducted at speeds of 14–16 km/h revealed a significant correlation between the aggregate's velocity and the quality of soil crumbling.

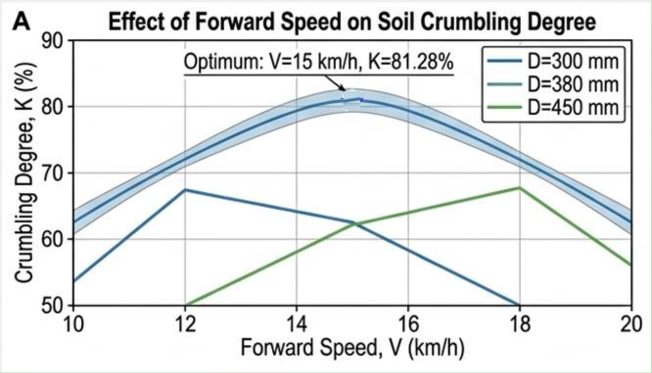

Figure 2: Impact of forward speed on soil crumbling degree (K, %)

As illustrated in Fig.2, the relationship between the aggregate's forward speed (V) and the quality of soil fragmentation was analyzed for different rotor diameters (D). The results indicate that for the optimal diameter of 380 mm, the crumbling degree reaches its peak value of 81.28% at a speed of 15 km/h. Speeds exceeding 18 km/h lead to diminishing returns in fragmentation quality, while lower speeds fail to provide sufficient kinetic energy for clod disintegration.

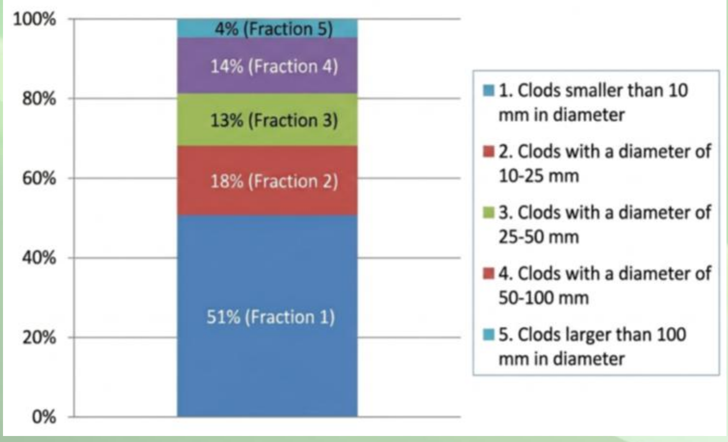

Figure 3. Degree of clod fragmentation

Figure 3 provides a comparative analysis of the soil fraction distribution between the proposed flexible cable-driven harrow and traditional rigid-axle implements. The results confirm that the new design produces a superior seed-bed structure, with 51% of the soil consisting of the 'active fraction' (<10 mm). Furthermore, the presence of large clods (>100 mm) is minimized to only 4%, whereas traditional spring-tooth harrows exhibit significantly higher clod retention in heavy clay-loam soils.

The high percentage of fine fractions (51%) is particularly noteworthy. From an agrotechnical perspective, this "active fraction" ensures maximum contact between the seed and the soil, which is a critical factor for uniform germination and moisture retention. The minimal presence of large clods (4%) indicates that the flexible rotors, operating at a 45° attack angle, effectively disintegrate hardened soil structures through high-frequency impact and rotation.

Evaluation of working depth and statistical stability. The average cultivation depth recorded during the trials was 7.72 cm, with a range of 5–10 cm depending on the field's micro-relief. One of the most important findings is the stability of this depth, which is attributed to the flexible cable connection of the rotors. Unlike rigid axles that tend to "jump" over obstacles, the cable allows the rotors to follow the soil's natural contours.

Statistical processing of the depth measurements (n=50 points) yielded the following metrics:

- Standard deviation (σ): 1.1 cm
- Coefficient of variation (V): 14.25%
- Experimental precision (P): 2.85%

A coefficient of variation of 14.25% in heavy soil conditions is considered excellent for high-speed implements. It demonstrates that the flexible design provides a more uniform cultivation layer compared to traditional rigid rotary harrows, which often exhibit variation coefficients exceeding 20% in similar conditions.

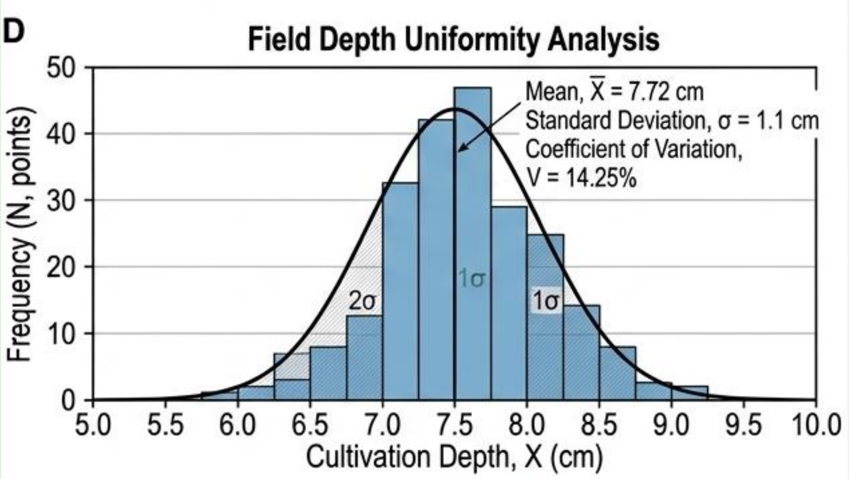

Figure 4. Statistical distribution of cultivation depth uniformity

The precision of the harrowing process was verified through a frequency distribution analysis of the cultivation depth (Fig.4). Based on 50 measurement points, the arithmetic mean (X) was determined to be 7.72 cm. The calculated Standard Deviation (σ) of 1.1 cm and a Coefficient of Variation (V) of 14.25% demonstrate high stability and uniformity in depth control, even across varying field micro-reliefs. The relative precision of the experiment stands at P=2.85%, ensuring a high level of scientific confidence.

Optimization of structural parameters. The relationship between rotor diameter (D), operating speed (V), and crumbling quality was modeled using regression analysis. The results indicate that the optimal performance point is located at D = 380 mm and V = 15 km/h.

At speeds below 12 km/h, the kinetic energy of the rotors is insufficient to overcome the soil's internal cohesion, leading to larger clods. Conversely, increasing the speed beyond 18 km/h causes excessive soil "dusting" (pulverization below 1 mm), which can lead to wind erosion and surface crusting. Therefore, the identified parameters represent a balanced "technological window" that maximizes productivity without compromising soil health.

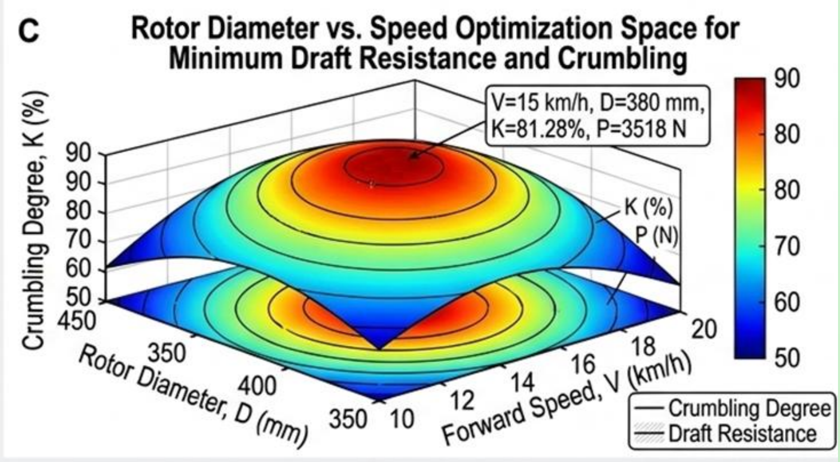

Figure 5. 3D Surface optimization for structural and kinematic parameters

To identify the most efficient operating window, a 3D response surface model (Fig.5) was generated to correlate rotor diameter, speed, and draft resistance (P). The optimization analysis confirms that the coordinate point of V=15 km/h and D=380 mm serves as the 'Golden Ratio,' yielding maximum fragmentation while maintaining a manageable draft resistance of 3518 N for tractors in the 1.4 draft class.

Energy and economic trade-offs. The reduced draft resistance (3518.1 N) directly impacted the fuel efficiency of the Belarus-892 tractor. The flexible connection reduces the peak shock loads on the tractor's transmission by absorbing sudden resistance changes through the cable's elasticity. This mechanical advantage resulted in a 55.3% reduction in operational costs.

When compared to conventional methods, the labor intensity was reduced by 62.3%, primarily due to the increased working width (3.5 m) and higher operating speeds. The annual economic effect of 7783.7 AZN per unit confirms that the initial investment in this innovative design is recovered within the first two seasons of intensive use.

Conclusion

Based on the complex theoretical and experimental research conducted on the innovative flexible cable-driven rotary harrow, the following comprehensive conclusions were reached:

- **Technological superiority:** The integration of a flexible cable-chain connection for the working organs allows for 100% adaptation to the soil micro-relief. Experimental trials confirmed that the optimal performance is achieved at an operating speed of 15 km/h with a rotor diameter of 380 mm. Under these conditions, the average cultivation depth was maintained at 7.72 cm.
- **Agrotechnical quality:** The harrow demonstrated exceptional soil-crumbling capabilities. The degree of soil fraction fragmentation reached 81.28%, which significantly exceeds standard requirements. Notably, 51% of the soil was reduced to the most desirable seed-bed fraction of <10 mm, ensuring optimal seed-to-soil contact and moisture preservation.
- **Statistical Reliability:** The mathematical processing of experimental data proved the high precision of the research. With a standard deviation of $\sigma = 1.1$cm and a coefficient of variation of $V = 14.25\%$, the relative error was kept at a minimal $m = 0.22$cm. The overall experimental precision was recorded at $P = 2.85\%$, validating the reliability of the proposed model.
- **Economic Impact:** The transition from rigid-axle harrows to the flexible cable-driven system provides substantial economic benefits. The research identified a 62.3% reduction in labor intensity and a 55.3% decrease in operational expenses. These improvements translate to an annual economic effect of **7**,783.7 AZN per machine, based on the reduction of reduced costs.
- **Practical Application:** The flexible cable harrow is highly effective for high-speed pre-sowing preparation, particularly in regions with heavy clay soils. Its implementation contributes directly to the national strategic goal of increasing wheat productivity by 10-15% and reaching the 5-million-ton annual grain production target.

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