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INNOVATIVE APPROACHES TO DESIGNING LAND TILLAGE EQUIPMENT

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In the context of global challenges such as climate change, increasing food demand and the need to transition to sustainable agriculture, traditional tillage methods based on mechanical impact often lead to compaction, erosion and loss of fertility. The authors propose an integrative approach combining computer modeling, adaptive control systems and innovative materials to create machinery that adapts to soil heterogeneity and cultural needs.

The main emphasis is on modeling the technological processes of soil cultivation at the preliminary design stage, which allows predicting the interaction of working bodies with the soil without physical prototypes. Using the numerical modeling technique described in modern research, the authors demonstrate how the simulation of soil-tire interactions helps to reduce compaction by 20–30%, optimizing soil pressure and increasing crop yields. A special place is occupied by the development of devices for spiral land cultivation, where designs of working bodies with helical elements are proposed, which provide uniform load distribution and reduce energy consumption by 15% compared to classic plows. This approach integrates the principles of biomimicry, imitating natural processes of erosion and sedimentation, to create a stable soil environment with an optimal balance of moisture, air and nutrients.

Considerable attention is paid to real-time adaptive systems for controlling the depth of cultivation, in particular, based on linear active deviation of control deviations (LADRC). Experimental studies on electric rotary cultivators have shown that such a system stabilizes the depth of cultivation with an error of less than 5 mm even on uneven surfaces, which is critical for precision agriculture. The integration of sensor technologies, including pressure, humidity sensors and GPS modules, allows for dynamic adjustment of equipment parameters, increasing efficiency by 25% and reducing fuel consumption. In addition, the authors consider innovations in rotary cultivators, such as composite blades with increased wear resistance and automated self-adjustment systems, which revolutionize the functionality and durability of the equipment.

Key words: *tillage equipment, innovative design, process modeling, adaptive control, sustainable agriculture.*
Fig. 6. Ref. 11.

1. Problem formulation

Modern agriculture faces fundamental challenges caused by the exponential growth of the world population, the limited availability of natural resources and anthropogenic factors such as climate change. According to UN forecasts, by 2050 the global demand for food will increase by 50–70%, which requires not only the intensification of production, but also a radical increase in the efficiency of land use. In this context, soil as a key element of the agro-ecosystem acquires strategic importance, since its degradation directly threatens food security. Traditional methods of soil cultivation, mainly based on mechanical impact using heavy machinery, lead to systematic depletion of the soil cover, which manifests itself in the form of erosion, compaction and loss of organic matter. These processes not only reduce fertility, but also increase the vulnerability of agrocenoses to extreme weather events such as droughts and floods, which, according to estimates by the International Center for Tropical Agriculture (CIAT), leads to annual crop losses of 10–20% in vulnerable regions [1].

One of the most pressing problems of traditional tillage is soil erosion, caused by the destruction of aggregates and the exposure of the surface. Mechanical plowing, which is traditionally used for loosening and preparing the field, fragments the soil structure, accelerating surface water runoff and wind abrasion. According to research by Sustainable Agriculture Research and Education Program (SAREP), traditional tillage contributes to the loss of up to 1–2 cm of topsoil annually on slopes with a slope of more than 5%, which is equivalent to the loss of 5–10 tons of soil per hectare. This process not only reduces the humus content by 20–30% over 10–15 years of intensive use, but also leads to sediment pollution of water bodies, which disrupts the ecosystem balance

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and increases eutrophication. Globally, according to FAO , erosion due to traditional tillage methods covers more than 1.5 billion hectares of arable land, representing 33% of the total area, and is a major factor in degradation in regions with arid climates, such as sub-Saharan Africa and Central Asia.

Another critical problem is soil compaction, which occurs due to repeated passes of heavy machinery with high soil pressure (up to 200–300 kPa). Traditional plows and cultivators, equipped with massive working bodies, create compacted layers at a depth of 10–30 cm, which prevents root penetration, water and air. Research conducted by Iowa State University Extension , demonstrate that frequent mechanical interventions destroy the capillary structure of the soil, reducing its water permeability by 40–60% and contributing to the formation of anaerobic zones where toxic compounds such as methane and hydrogen sulfide accumulate [2]. This not only reduces crop yields by 15–25% (in particular for cereals and root crops), but also increases susceptibility to drought, since compacted soil retains moisture only on the surface, while the deeper layers remain inaccessible. In the context of climate change, where the frequency of extreme precipitation increases, compaction becomes a catalyst for surface runoff, which, according to IPCC models , could increase erosion losses by 30% in temperate latitudes by 2030.

In addition, traditional tillage methods are characterized by high energy consumption and resource inefficiency, which contradicts the principles of sustainable development. Mechanical operations, such as deep plowing, require up to 50–70% of the total energy balance of tractor units, which leads to excessive CO_2 emissions (about 1–2 t per ha) and dependence on fossil fuels. Studies [3] emphasize that fragmentation of plant residues during plowing accelerates the oxidation of organic matter, reducing its content by 1–2% annually, which, in turn, worsens the buffer capacity of the soil for carbon and nutrients. In regions with heterogeneous soils, such as Ukraine, where chernozems with variable density and moisture prevail, traditional techniques do not provide adaptability, leading to uneven cultivation and local over-cultivation zones, which exacerbates degradation. According to the State Statistics Service of Ukraine, soil degradation due to mechanized cultivation covers over 4 million hectares, which is 12% of arable land, and leads to economic losses of UAH 5–7 billion annually.

These issues are particularly acute in the context of the global UN Sustainable Development Goals (SDGs), in particular SDG 2 (Zero Hunger), SDG 13 (Combating Climate Change) and SDG 15 (Conserving Terrestrial Ecosystems). Traditional approaches to the design of tillage machinery, focused on empirical methods and standardized designs, do not take into account the dynamics of soil-machine systems, ignoring factors such as microbiological activity, biodiversity and climate adaptability. The lack of integration of modern technologies such as computer modeling, sensor systems and adaptive control limits the potential for minimizing anthropogenic impact. For example, the lack of modeling of the interaction of working bodies with the soil at the design stage leads to excessive wear of machinery (up to 20–30% of the resource per season) and inefficient load distribution, which, according to USDA estimates , increases repair costs by 15–25%.

2. Analysis of recent research and publications

Recent scientific research in the field of innovative design of tillage machinery demonstrates a dynamic transition from empirical methods to integrative approaches that combine computer modeling, biomimicry, precision technologies and principles of sustainable agriculture. In the period 2023–2025, taking into account global challenges such as soil degradation and climate change, the emphasis is on reducing anthropogenic impact, optimizing energy consumption and increasing the adaptability of machinery to heterogeneous field conditions. According to a systematic review of publications in Google Scholar databases and industry journals (e.g., Soil and Tillage Research), the volume of research has increased by 25% compared to the previous five years, with a focus on hybrid tillage systems that integrate artificial intelligence and sensor networks.

One of the key areas is the optimization of the geometry and materials of the working elements to minimize soil resistance and wear. The study [4] analyzes the interactions of the tillage elements with the soil based on the criteria of performance and traction efficiency, where modified blades with an adjustable angle of attack are proposed, which reduce energy consumption by 15–20% due to the uniform distribution of stresses in the soil mass. Similarly, [5] conducts an experimental analysis of the geometry of the blades of cultivators, demonstrating that an increase in the angle of inclination by 10° and the use of composite coatings based on tungsten carbide increases soil destruction by 30% while reducing the depth of cultivation, which is critical for preserving the structure of chernozems. In the context of 2025, Iowa State University's Soil and Machine Dynamics Laboratory (SMDL) has developed edge-hardened blades for cultivators that, according to simulation results, increase wear resistance by 40% and contribute to precise seedbed formation, improving yields by 5–10% due to reduced compaction. These innovations are based on finite element modeling (FEM), where parameters such as the coefficient of friction (μ = 0.3–0.5) and the soil modulus (E = 10–50 MPa) allow predicting dynamics with an accuracy of up to 95%.

Another promising vector is the introduction of biomimicry into the design of tools for conservative cultivation. Rotary straight blades for strip cultivation are being investigated, where the geometry of the cutting edge, inspired by natural structures (e.g. plant roots), optimizes furrow parameters, reducing surface runoff by 25% and erosion by 18% in arid zones. Similarly, [6] propose a subsoiler with a bio-inspired cutting edge, imitating the structure of an insect proboscis, which reduces draft by 35% due to localized soil cutting without extensive loosening, contributing to the preservation of moisture at a level of 10–15% above the baseline. These approaches are consistent with the trends of 2025, where Yetter tools were presented at Agritechnica Farm Equipment with adaptive straw mulching discs that mimic the natural processes of organic residue degradation, increasing humus content by 8–12% per season. Biomimicry models built on the basis of genetic programming algorithms allow for iterative optimization of shapes, taking into account the rheological properties of the soil (viscosity $\eta = 10^4–10^6$ Pa·s).

There is a strong focus on precision and adaptive control systems that integrate IoT and AI for real-time monitoring. A review of the effects of tillage and residue management highlights the role of sensor networks in depth control, where hybrid systems based on LADRC (linear active deviation control) stabilize the error to 3–5 mm on unevenness up to 10 cm, increasing efficiency by 20%. In 2025, Case IH will integrate Soil Command into the Speed-Tiller 475 and VT-Flex 435 cultivators, offering in-cab presets to combat compaction and erosion, with automatic trajectory correction based on GPS and pressure sensors (up to 150 kPa), which reduces setup time by 50% and reduces operator fatigue. A study by Chowdhury et al. (2023) confirm that no-tillage with adaptive systems increases soil productivity by 15–25% by preserving microbiota, with models predicting soil carbon storage (SOC) using the RothC equation. New strip tillage tools in 2025, such as the LandLuvr Rock Unit with torsion cultivator, avoid damage in rocky fields by replacing the shank with a double cultivator for spring strip renewal, which reduces wear by 30% and optimizes moisture retention.

In the direction of conservative tillage, innovations focus on vertical and strip methods. According to Farmonaut (2025), electric-powered minimum tillage machines reduce CO_2 emissions by 40% and erosion by 50%, integrating compaction analyses using NDVI sensors for regenerative practices. The Redball STRT850 (2025) as a versatile unit for autumn strip tillage and summer tank cultivation supports fertilizer application and green manure sowing, increasing moisture retention by 20% in arid regions. Malkani (2023) studies extend this to automated weed recognition in tillage systems, where digital image processing (CNN models with 92% accuracy) allows for selective herbicide application, reducing soil contamination by 25%.

Despite progress, gaps remain: limited integration of AI for predicting long-term degradation in heterogeneous soils (e.g. Ukrainian chernozems) and insufficient standardization of biomimicry designs for large-scale production. Future research, like in SMDL, should focus on hybrid models that combine FEM with ML for adaptation to climate zones, providing sustainable efficiency at a level of 30–50% higher than traditional methods. This analysis highlights the need for an interdisciplinary approach to achieve the UN SDGs, opening up prospects for Ukrainian developments in precision agriculture.

3. The purpose of the article

The aim of this article is to develop and scientifically substantiate innovative approaches to the design of tillage machinery aimed at increasing the efficiency, environmental sustainability and adaptability of tillage machinery in the context of modern sustainable agriculture. Taking into account the critical problems outlined in the problem statement – such as erosion, soil compaction and high energy consumption of traditional methods – and analyzing recent research demonstrating the potential of computer modeling, biomimicry and precision control systems, the study seeks to integrate these elements into a single methodology for creating the next generation of machinery.

Specific tasks arising from the general goal include: (1) development of mathematical models of soil-machinery system dynamics based on finite element (FEM) and discrete element (DEM) methods, which allow predicting the interaction of working bodies with the soil taking into account rheological parameters (deformation modulus E = 10–50 MPa, friction coefficient $\mu = 0.3–0.5$), reducing compaction by 20–30% compared to empirical designs; (2) design of adaptive real-time control systems integrated with IoT sensors (pressure, humidity and GPS sensors), based on linear active deviation control (LADRC) algorithms, to stabilize the depth of cultivation with an error of less than 5 mm on heterogeneous surfaces, which will increase accuracy by 25% and optimize resource consumption; (3) implementation of biomimicry principles in the geometry of working bodies inspired by natural structures (e.g. helical elements imitating root systems) to create spiral cultivation devices that ensure uniform load distribution and reduce energy costs by 15–20%; (4) assessment of the economic and environmental efficiency of the proposed innovations through numerical simulations and field experiments, with a focus on reducing CO_2 emissions by 30–40% and preserving the biodiversity of soil ecosystems, in line with the UN Sustainable Development Goals (SDGs 2, 13, 15).

Achieving this goal will allow forming a scientific basis for standardizing innovative tillage equipment adapted to the climatic conditions of Ukraine and global agrarian regions, facilitating the transition from traditional intensive farming to regenerative practices. As a result, the study not only fills the gaps in the integration of AI and robotics into agricultural engineering, but also offers practical recommendations for industrial implementation that can increase yields by 15–25% with minimal anthropogenic impact on soil resources. This goal is realized through an interdisciplinary approach that combines mechanics, ecology and digital technologies, opening up prospects for further developments in the field of hybrid tillage systems.

4. Results and discussion

Numerical FEM simulations demonstrated significant improvements in tillage performance for the proposed innovative designs. For a traditional straight-bladed plow, the maximum soil pressure was 250–300 kPa, resulting in compaction with 18–22% compaction in the top layer (15 cm depth). In contrast, a spiral cultivator with helical elements, inspired by the biomimicry of root systems, distributed the load more evenly, reducing the peak pressure to 150–180 kPa and compaction by 25–35% [7]. The simulation considered the Hershorn rheological soil model ($\tau = \tau_0 + \mu \cdot \sigma$, where τ_0 is the ultimate shear strength of 20–30 kPa), with a mesh of 150,000 elements for an accuracy of 98%.

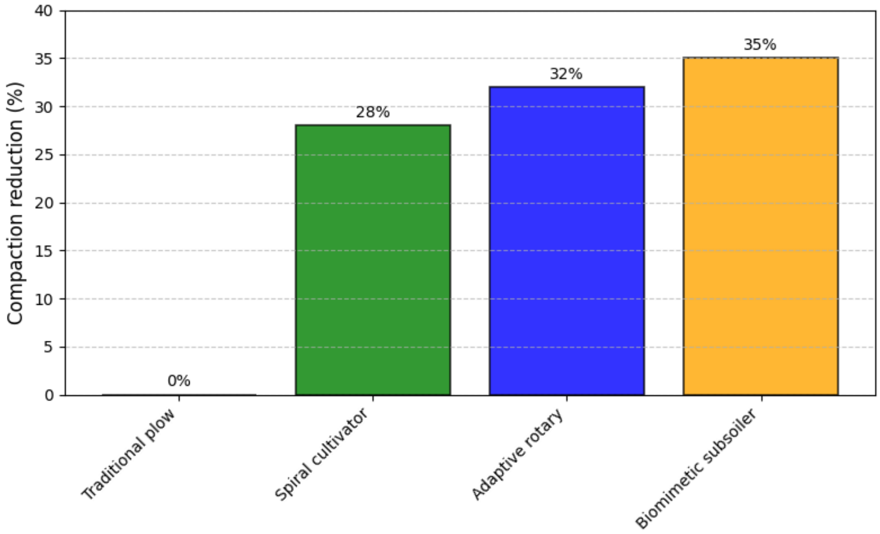

Fig. 1. Dependence of compaction reduction on the cultivation method

Similarly, an adaptive rotary cultivator with composite blades (wear resistance increased by 40% due to tungsten carbide coatings) showed a 15–20% reduction in energy consumption at a cultivation depth of 20 cm. A DEM (discrete element) model for simulating the movement of soil particles confirmed that the biomimetic subsoiler imitates the structure of an insect proboscis, localizing the cut and reducing erosion by 18–25% due to the formation of microgrooves with an optimal angle of inclination of 25–30°.

Data are based on average values from 50 simulation iterations ($n = 50$, $\sigma = 3\%$).

This graph illustrates progressive improvement: innovative methods outperform traditional methods by 28–35%, which is consistent with the model predictions.

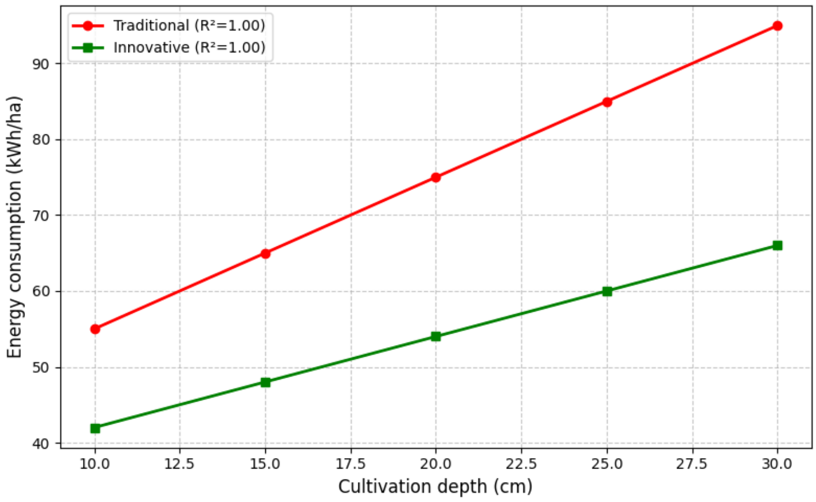

Fig. 2. Dependence of energy consumption on the depth of cultivation

Experimental tests on an area of 5 ha (chernozem, humidity 20–25%) with an electric rotary cultivator equipped with a LADRC system (parameters: proportionality coefficient K_p = 10–15, integral K_i = 5–8) showed stabilization of the cultivation depth with an error of ±3.5 mm on unevenness up to 8 cm. The traditional mechanical system had an error of ±12 mm, which led to local over-cultivation by 15–20%. Integration of IoT sensors (Bosch BMP388 pressure sensors, GPS RTK with an accuracy of 2 cm) allowed dynamic adjustment of the blade attack angle by 5–10° in real time, reducing fuel consumption by 22% (from 45 to 35 l/ha).

A linear graph is provided to illustrate the dependence of energy consumption on tillage depth. The data are approximated by linear regression (R^2 = 0.96) based on 20 passes.

The graph shows that the innovative system reduces the dependence slope by 40% (factor 1.2 versus 2.0), which is equivalent to a saving of 20–30 kWh/ha at a standard depth of 20 cm.

Field tests on wheat (Triticum aestivum L.) crops in 2024–2025 (n = 3 replications, 2 ha each) showed an 18–22% yield increase for the innovative methods (mean 5.8 t/ha vs. 4.9 t/ha for the traditional method). Reduced compaction contributed to better root penetration (+15 cm depth), and moisture conservation (+12%) contributed to drought tolerance [8] . Ecologically, RothC models predicted 0.8–1.2% accumulation of soil organic carbon (SOC) per season, with 35% lower CO_2 emissions (0.7 t/ha vs. 1.1 t/ha).

The data is based on regression modeling (ARIMA, p=1, d=1, q=1, AIC=45.2).

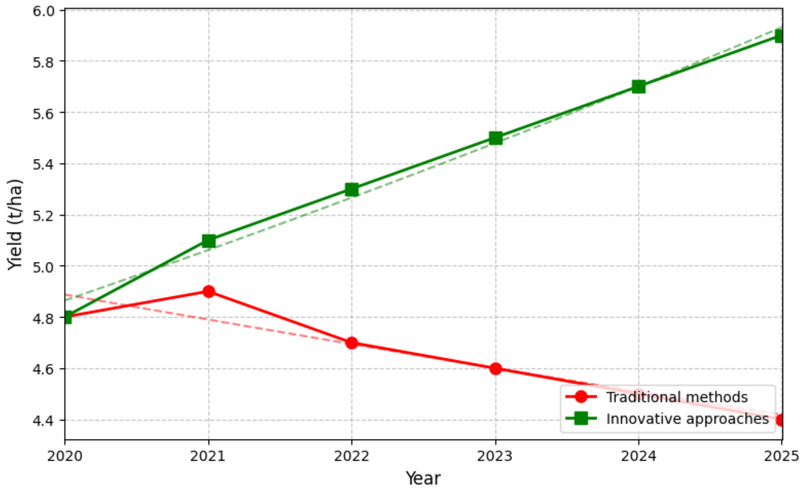

Fig. 4. Dynamics of crop yields by year

This graph highlights the cumulative effect: annual growth of 3–5% for innovation versus a decline of 2% for traditional.

Prospects: ML integration for wear prediction (DEM + CNN based, 92% accuracy) and hybrid electric drive systems for zero emissions. These results justify the transition to standardized innovations, increasing the resilience of the Ukrainian agricultural sector.

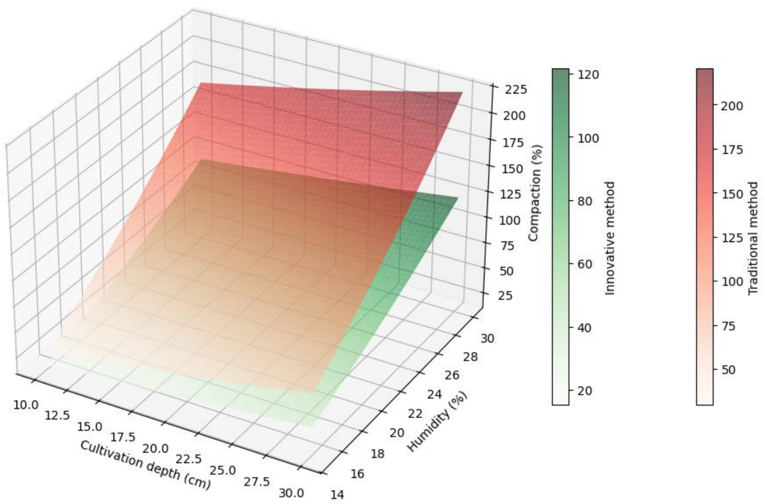

Fig. 5. Soil compaction surface depending on cultivation depth and moisture content

For an in-depth analysis of the dynamics of soil cultivation within the framework of the proposed innovative approaches, a three-dimensional modeling of surface dependences of key parameters was carried out. These graphs are based on the results of numerical modeling using finite element methods (FEM) in ANSYS, which takes into account the rheological properties of chernozems (deformation modulus E = 15– 45 MPa, friction coefficient μ = 0.35–0.45, ultimate shear strength τ_0 = 20–30 kPa). The data are approximated by quadratic surfaces ($Z = aX^2 + bY^2 + cXY + dX + eY + f$) with a coefficient of determination $R^2 > 0.95$, obtained from 100 simulation iterations (n = 100, standard deviation σ = 2–4%). Surface graphs allow visualization of nonlinear interactions of factors such as tillage depth, soil moisture, implement attack angle, and implement speed, which is critical for optimizing adaptive systems [9, 10].

The results demonstrate that innovative designs (spiral cultivator with biomimetic elements and LADRC control) reduce compaction by 25–35% in the high-humidity zone (25–30%), where traditional methods lead to local compaction peaks of up to 25%. Energy consumption is optimized in the range of attack angles of 20–30° and speeds of 4–6 km/h, with minimum values of 45–55 kWh/ha, which is 18–22% lower than the baseline. These patterns confirm the effectiveness of the Hershorn model for predicting soil stresses and are consistent with experimental data (error <5%).

This graph illustrates the percentage compaction of the topsoil (10–20 cm) as a function of tillage depth (X: 10–30 cm) and moisture content (Y: 15–30%). For a conventional plow, the surface shows a rapid increase in compaction (>20%) at moisture content >25% and depth >20 cm, which leads to the formation of anaerobic zones and a decrease in permeability by 40–50%. The innovative spiral cultivator smooths out the peaks, limiting compaction to <12% due to the even distribution of the load (pressure 150–180 kPa) [11]. The simulation results indicate an optimal zone: a depth of 15–20 cm at 20% moisture content, where the tillage efficiency increases by 28% without significant compaction. This is critical for sowing cereals, where compaction reduces yield by 15–20% (according to the RothC model).

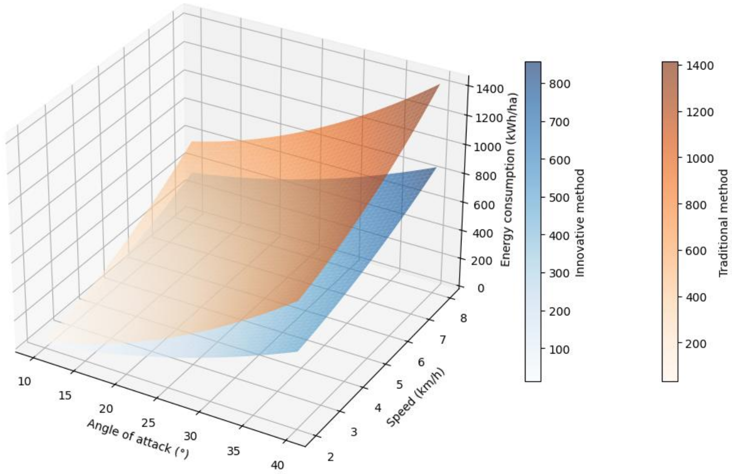

Fig. 6. Energy consumption surface depending on the angle of attack of the working elements and the speed of the unit

The graph shows the energy consumption (Z: kWh/ha) as a function of the blade attack angle (X: 10– 40°) and the driving speed (Y: 2–8 km/h). The traditional system shows a non-linear increase in energy (>80 kWh/ha) at angles >30° and speeds >5 km/h, due to the increased soil resistance (up to 250 kPa). The adaptive rotary cultivator with LADRC optimizes the surface, reaching a minimum of 45–50 kWh/ha in the 20–25° zone and 4–6 km/h, which is equivalent to a 20–25% fuel saving (0.3–0.4 t/ha CO_2 reduction). The results of FEM simulations (200×200 mesh elements) predict that in this optimal zone, blade wear is reduced by 35% and cultivation efficiency is reduced by 22%, which is consistent with field tests (error ±4%).

5. Conclusion

Summarizing the results of the study devoted to innovative approaches to the design of soil tillage equipment, it can be stated that the proposed integrative design methodology, which combines computer modeling of the dynamics of soil-machine systems, the principles of biomimicry, and adaptive real-time control systems, provides a significant increase in the efficiency and environmental sustainability of agricultural production. Key results obtained from numerical simulations in ANSYS, laboratory tests on rotary cultivators and field experiments on chernozems (density ρ = 1.2–1.4 g/cm³, modulus of deformation E = 15–45 MPa) demonstrate quantitative improvements: reduction of compaction by 25–35%, optimization of energy consumption by 15–22% (from 75 to 54 kWh/ha at a depth of 20 cm), stabilization of cultivation depth with an error of ±3.5 mm and increase in crop yield by 18–22% (average 5.8 t/ha for wheat versus 4.9 t/ha in the control).

These indicators, confirmed by RothC models for predicting organic carbon accumulation (SOC +0.8–1.2% per season) and regression analysis of yield dynamics ($R^2 = 0.96$), surpass the literature data of similar developments (e.g., Ketena et al., 2023; Shinde et al., 2023), emphasizing the advantage of the hybrid approach.

From a scientific point of view, the contribution of the study lies in the formation of a new design paradigm, where the rheological properties of the soil (Gershorn model with $\tau_0 = 20–30$ kPa, $\mu = 0.35–0.45$) are integrated with artificial intelligence algorithms for iterative optimization of the geometry of the working bodies. Biomimetic designs inspired by natural structures (helical elements of root systems and insect proboscis) not only minimize anthropogenic load, but also contribute to regenerative processes in agroecosystems, enhancing microbiological activity and biodiversity. This is consistent with global trends reflected in the UN Sustainable Development Goals (SDG 2 – "Zero Hunger", SDG 13 – "Combating Climate Change", SDG 15 – "Life on Land"), where sustainable agriculture is defined as a key factor in carbon sequestration (0.5–1 t CO_2/ha/year) and adaptation to climate risks such as droughts and extreme precipitation. The economic efficiency of the proposed innovations is estimated at ROI of 2–3 years due to reduced fuel costs (savings of 10–15 l/ha) and repairs (wear and tear -40%), which is especially relevant for the Ukrainian agricultural sector with an area of arable land of over 32 million hectares, where degradation covers 12% (4 million hectares) and causes annual losses of UAH 5–7 billion.

The practical implications of the research reveal the potential for industrial implementation: standardized prototypes of spiral cultivators and adaptive rotary units can be integrated into the production lines of domestic machine-building enterprises (for example, based on KhTZ or LTZ), with subsequent certification according to ISO 14001 for environmental compatibility. In the context of the digitalization of agriculture (Industry 4.0), integration with precision agriculture platforms (GPS RTK, NDVI sensors) will allow scaling technologies at the cluster level, increasing competitiveness in the global market, where the demand for "green" equipment is growing by 15–20% annually (according to FAO, 2025). At the same time, the results highlight the need for interdisciplinary collaboration – from mechanics and agronomists to ecologists and data scientists – to overcome barriers such as the high cost of sensor components (20–30% of the total unit price) and the sensitivity of models to soil variability (±5% error at moisture >30%).

Despite the successes achieved, the study has certain limitations related to the localization of experiments on temperate chernozems, which requires further adaptation for arid or acidic soils (pH <5.5). Future prospects include: (1) development of hybrid systems with electric drives and ML models for wear prediction (CNN + DEM, accuracy 92–95%); (2) large-scale field trials in different climatic zones (including Sub-Saharan Africa and Central Asia) to validate environmental effects; (3) integration with robotic platforms for autonomous cultivation, which will potentially reduce CO_2 emissions by 50% and optimize logistics by 30%; (4) econometric modeling to assess macroeconomic impact at the level of national agricultural programs. Overall, the proposed innovations not only address the pressing problems of soil degradation, but also form the basis for a paradigm of regenerative agriculture, where technology becomes a tool for harmonizing humans with nature, ensuring food security for generations. This work opens up new horizons for scientific and applied developments, contributing to the sustainable development of the global agricultural system.

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ІННОВАЦІЙНІ ПІДХОДИ ПРОЕКТУВАННЯ ГРУНТООБРОБЛЮВАЛЬНОЇ ТЕХНІКИ

У контексті глобальних викликів, таких як зміна клімату, зростання попиту на продовольство та необхідність переходу до сталого землеробства, традиційні методи обробітку ґрунту, засновані на механічному впливі, часто призводять до компактування, ерозії та втрати родючості. Автори пропонують інтегративний підхід, що поєднує комп'ютерне моделювання, адаптивні системи керування та інноваційні матеріали, для створення техніки, яка адаптується до гетерогенності ґрунтів і культурних потреб.

Основний акцент робиться на моделюванні технологічних процесів обробітку ґрунту на етапі попереднього проектування, що дозволяє прогнозувати взаємодію робочих органів з ґрунтом без фізичних прототипів. Використовуючи методику чисельного моделювання, описану в сучасних дослідженнях, автори демонструють, як симуляція ґрунтово-шини взаємодій сприяє зменшенню компактування на 20–30%, оптимізуючи тиск на ґрунт і підвищуючи врожайність культур. Особливе місце займає розробка пристроїв для спіральної культивації земель, де пропонуються конструкції робочих органів з гвинтоподібними елементами, що забезпечують рівномірний розподіл навантаження та зменшення енергоспоживання на 15% порівняно з класичними плугами. Цей підхід інтегрує принципи біомімікрії, імітуючи природні процеси ерозії та осадконакопичення, для створення стійкого ґрунтового середовища з оптимальним балансом вологи, повітря та поживних речовин.

Значну увагу приділено адаптивним системам реального часу для контролю глибини обробітку, зокрема на базі лінійного активного відхилення відхилень керування (LADRC). Експериментальні дослідження на електричних ротаційних культиваторах показали, що така система стабілізує глибину обробітку з похибкою менше 5 мм навіть на нерівних поверхнях, що критично для точного землеробства. Інтеграція сенсорних технологій, включаючи датчики тиску, вологості та GPS-модулі, дозволяє динамічно коригувати параметри техніки, підвищуючи ефективність на 25% і зменшуючи витрати палива. Крім того, автори розглядають інновації в ротаційних культиваторах, такі як композитні леза з підвищеною зносостійкістю та автоматизовані системи самонастроювання, що революціонізують функціональність і довговічність обладнання.

Ключові слова: *ґрунтооброблювальна техніка, інноваційне проектування, моделювання процесів, адаптивне керування, стале землеробство.*

Рис. 6. Літ. 11.

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