AGROLOGY

ISSN 2617-6106 (print)
ISSN 2617-6114 (online)
Agrology, 2025, 8(1), 48–54
doi: 10.32819/202507

Original researches

Received: 05.01.2025
Revised: 01.02.2025
Accepted: 09.03.2025

Dnipro State Agrarian
and Economic University,
Serhii Efremov St., 25,
Dnipro, 49600, Ukraine.
Tel.: +38-056-371-08-21.
E-mail: tkalich_yuriy@ukr.net

Cite this article: Tsyliuryk, O. I., Tkalich, Y. I., Kolesnykova, K. V., Rudakov, Y. M., & Tkalich, Y. Y. (2025). Modern trends and development directions of soil tillage systems in the world and Ukraine. Agrology, 8(1), 48–54. doi: 10.32819/202507

Modern trends and development directions of soil tillage systems in the world and Ukraine

O. I. Tsyliuryk*, Y. I. Tkalich*, K. V. Kolesnykova, Y. M. Rudakov *. Y. Y. Tkalich***
**Dnipro State Agrarian and Economic University, Dnipro, Ukraine*
***Dnipro-Oril Nature Reserve, Obukhivska village council, Dnipropetrovsk Oblast, Ukraine*

Abstract. The development of soil tillage systems is one of the key factors determining the efficiency of agricultural production, its sustainability, and environmental safety. Over the past decades, global trends in the agricultural sector have increasingly focused on implementing innovative tillage methods aimed at reducing mechanical impact, preserving natural fertility, and optimizing the use of energy and material resources. In particular, these include minimal tillage, no-till, and strip-till technologies, which can mitigate erosion, enhance moisture conservation, and boost soil microbiological activity. In countries with arid climates and degraded soils, these methods are essential for maintaining sustainable agriculture. In Ukraine, soil tillage systems are undergoing significant transformations under the influence of climate change, economic factors, and the need to enhance the efficiency of agricultural production. The growing moisture deficit, soil depletion, and the necessity to reduce fuel and lubricant costs are driving agricultural enterprises to actively implement minimal tillage, use combined implements, and adopt wide-span machinery. Direct seeding and precision farming technologies are also becoming promising tools for optimizing agronomic practices. However, the effectiveness of these methods depends on natural and climatic conditions, soil type, and the level of agronomic support, requiring further scientific research and technological adaptations to regional specifics. This article analyzes current global and Ukrainian trends in the development of soil tillage systems, their effects on the physical and chemical properties of soils, the productivity of agricultural crops, and the economic feasibility of implementing advanced technologies. Special attention is given to assessing the environmental consequences of different tillage systems, particularly their effects on soil humus content, water balance, weed infestation levels, and the phytosanitary status in agricultural ecosystem. The study also explores the prospects for using adapted tillage technologies in the context of climate change and economic instability, which are crucial factors for ensuring the sustainable development of Ukraine's agricultural sector.

Keywords: tillage; soil agrophysical indicators; soil fertility; water regime; weed management; energy conservation.

Introduction

The modern development of soil tillage systems is characterized by significant technological and methodological changes aimed at increasing the efficiency of agricultural production, preserving soil resources, and minimizing negative environmental impacts. Innovative digital technologies and automated management systems create new opportunities for precise monitoring of the physicochemical properties of soil, enabling farmers to respond promptly to changes in the soil ecosystem. The use of satellite monitoring, GPS navigation, and specialized sensors ensures continuous control of moisture levels, temperature regimes, and nutrient content, allowing for the optimization of fertilizer application rates and the use of plant-protection products (Caputo, 2022).

In modern agricultural ecosystem, precision-farming methods are being actively implemented, complementing traditional tillage approaches with advanced technologies. This allows for precise regulation of tillage parameters, taking into account local soil characteristics and variable climatic conditions. As a result, both soil structure and its water permeability are improved, which is a key factor in creating a favorable microclimate within agroecosystems (Akhter et al., 2022).

The intensification of agriculture is accompanied by the widespread use of modern agrochemicals, including fertilizers, pesticides, soil ameliorants, and measures to combat erosion processes. However, primary soil tillage remains a key component in field preparation for sowing, as it ensures the uniform distribution of nutrients and creates favorable conditions for the development of root system. Traditional methods, such as moldboard plowing, combined with modern approaches, particularly no-till technologies, contribute to preserving the upper organic layer and maintaining soil biological activity (Manlay et al., 2022).

Soil conservation measures are becoming particularly relevant in the context of climate change, as erosion processes intensify and the pressure on agricultural ecosystems increases. The use of mulching, including cover crops, and the implementation of no-till soil management technologies help minimize surface runoff of rainwater and reduce the risk of soil degradation. Modern agricultural machinery, equipped with artificial intelligence systems, enables precise regulation of machine operations, contributing to energy savings and reducing mechanical impact on the soil (El-Beltagi et al., 2022).

The continuous improvement of soil tillage technologies is accompanied by active scientific research and the development of new methods that take into account both the agrochemical properties of soils and the climatic characteristics of the region. Data obtained from modern sensor networks are used to build analytical models that enable the prediction of changes in soil properties, as well as the timely adjustment of technological processes. This enhances the precision of agricultural practices and ensures a more rational use of natural resources (Kumar et al., 2024).

Modern soil tillage technologies and the challenges of their application in current conditions

Modern soil tillage technologies, particularly new tillage implements designed for use in various natural and climatic conditions, aim to enhance the efficiency of agricultural practices, improve the physical and chemical properties of the soil, and ensure an optimal water, air, and nutrient regime for crops. However, their application in heterogeneous soil-cover conditions, with variability in mechanical composition, moisture availability, and regional climatic factors, does not always achieve the desired tillage quality. Often, modern technical solutions do not fully address the set objectives due to several factors, including insufficient loosening efficiency, limited improvement of soil structure, low surface leveling quality, inadequate weed control, and imperfect regulation of the soil's water-air balance.

One of the main challenges associated with the use of modern tillage implements is insufficient soil loosening and fragmentation. Heavy and compacted soils require deep loosening to improve water and air permeability, but not all implements can provide the necessary level of aeration. Excessive compaction of the arable layer leads to the formation of a plow pan, which negatively affects crop root growth, reduces the efficiency of water and nutrient uptake, and impairs overall soil health. Moreover, under moisture-deficient conditions, excessive loosening accelerates water evaporation, potentially leading to the drying of the upper soil layer.

Another important aspect is the uneven soil structure after tillage. An optimal structure ensures resistance to water and wind erosion, preservation of organic matter, and favorable conditions for the development of beneficial microorganisms. However, in soils with heterogeneous mechanical composition, tillage implements may either excessively pulverize soil particles or leave large clumps, reducing the overall quality of field preparation for sowing.

Surface leveling plays a crucial role in ensuring crop productivity. The presence of irregularities and ridges after tillage leads to uneven seed distribution during sowing, which negatively affects seedling uniformity and plant spacing within the seeding layer. Additionally, field unevenness creates obstacles for mechanized crop management, increases the risk of water erosion, and complicates moisture regulation in the upper soil layer.

Another challenge to modern tillage technologies is weed control, since mechanical methods do not always effectively eliminate them. Some weed species, particularly perennials, can quickly regenerate after tillage, requiring additional agronomic measures. Incomplete weed removal leads to their active growth and competition with crops for moisture, nutrients, and sunlight, ultimately reducing the productivity of agricultural ecosystem.

Moreover, modern tillage implements often fail to fully optimize the regulation of the soil's water-air balance. An improperly selected tillage method can lead to either excessive compaction or, conversely, excessive loosening, which hinders the accumulation and retention of moisture in the arable layer. This issue is particularly relevant in arid regions, where soil moisture conservation is a key factor in ensuring stable crop yields.

Thus, modern soil tillage technologies offer numerous advantages, but their effectiveness largely depends on the conditions of application. To ensure high-quality tillage, it is necessary to improve technical equipment, optimize technological processes, adapt tillage methods to specific natural and climatic conditions, and integrate mechanical, chemical, and biological measures to enhance the resilience of agroecosystems and the productivity of agricultural crops.

In this regard, modern tillage technologies do not always ensure the required quality of soil loosening, leveling, and structuring, nor do they fully meet the expected objectives. To address these challenges, continuous improvements are being made in the key aspects of soil tillage:

a) resource and energy conservation, which includes saving fuel and lubricants, reducing the enormous amount of energy required for soil tillage, as well as optimizing time and labor resources. Resource and energy conservation in modern agriculture are crucial factors that enhance the economic efficiency of agricultural production while minimizing its negative environmental impact. One of the key aspects of this process is reducing fuel and lubricant consumption, achieved through the implementation of minimum tillage and no-till technologies, optimization of agronomic practices, and the use of modern high-performance machinery. Decreasing the number of mechanical operations and machinery passes across the field not only reduces the fuel costs but also significantly lowers the overall energy expenditures for fieldwork. Additionally, reducing tillage depth helps preserve the soil structure, prevents excessive moisture evaporation, and minimizes the destructive impact on soil microorganisms, which in turn positively affects soil fertility (Majeed et al., 2023). A crucial factor in improving energy efficiency is the use of wide-coverage machinery and combined implements, which allow multiple operations to be performed in a single pass – for example, simultaneously loosening the soil, leveling the field surface, compacting the soil, and applying fertilizers. This not only significantly reduces the fuel consumption but also saves time, which is especially important during peak fieldwork periods when every day impacts the final crop productivity. Rapid and high-quality execution of agricultural practices helps maintain optimal conditions for plant growth and development, prevents yield losses, and ensures uniform crop development within the crop rotation system (Fussy et al., 2022).

The use of resource-saving technologies promotes the efficient utilization of labor resources, as modern machinery enables the automation of most tasks, thus reducing the need for a large workforce. This is particularly relevant in the context of a shortage of skilled labor in the agricultural sector. By lowering labor costs and reducing the physical workload on personnel, overall agricultural productivity increases, allowing farms to allocate their financial and material resources more effectively;

b) moisture accumulation and retention. This is one of the most important tasks of modern agriculture, especially in the arid climate of the Steppe, where moisture deficiency significantly affects the productivity of agroecosystems and the final yield of agricultural crops. Soil moisture conservation is a complex process that depends not only on precipitation levels but also on the physicochemical properties of the soil, its structure, the chosen tillage system, and agronomic practices aimed at reducing evaporation and ensuring optimal conditions for plant growth (Lykhovyd et al., 2021).

One of the most effective methods for regulating soil water balance is mulch tillage, which involves covering the soil surface with a layer of shredded plant residues. This creates a natural protective barrier that significantly reduces moisture evaporation under high temperatures and wind exposure. This technology not only helps conserve productive moisture reserves but also prevents water and wind erosion, as the mulch layer prevents soil compaction caused by rainfall and facilitates the accumulation of precipitation in deeper soil horizons (Meyer et al., 2021).

With mulch tillage, soil water permeability is significantly improved, which is particularly important in the conditions of uneven precipitation distribution. Moisture not only accumulates more efficiently but is also retained for a longer period, allowing plants to utilize it more effectively throughout the entire growing season. Moreover, the mulch layer stimulates biological processes in the soil, enhances microbial activity, and improves soil structure, which positively affects its fertility (Tsyliuryk et al., 2022).

In the arid conditions of the Steppe, where evaporation significantly exceeds precipitation, the application of mulch tillage is an essential component of an effective agricultural crop production technology. Using this method in combination with other agronomic practices not only helps conserve soil moisture reserves but also enhances the resilience of agroecosystems to adverse weather conditions, ensures uniform plant development, and contributes to stable yields even in dry years (Gavrilescu et al., 2021; Tsoraeva et al., 2021; El-Beltagi et al., 2022);

c) combating erosion processes (water erosion, deflation). Addressing erosion processes, particularly water erosion and deflation, is a critical challenge in modern agricultural production, as soil degradation leads to significant losses in fertility, reduced crop yields, and disruptions in ecological balance. One of the most effective methods for preventing erosion is the retention of plant residues from previous crops on the soil surface, which ensures maximum protective coverage and creates a natural barrier against the destructive impact of wind and water. This agronomic practice plays an especially crucial role in open, wind-exposed areas where windbreaks are either absent or insufficiently developed, increasing the risk of deflation, particularly during periods of strong winds and unstable weather conditions (Fan et al., 2023).

Plant residues left on the field after harvest serve several important functions: they create a mechanical barrier that prevents the top fertile soil layer from being blown away by the wind, promote even moisture distribution, and reduce the intensity of surface runoff during heavy rainfall or rapid snowmelt at the end of winter or in early spring. During these periods, when the soil has not yet fully frozen or thawed, a significant amount of water can quickly run off the fields, washing away the fertile layer and leading to the formation of gullies. Covering the soil with plant residues helps mitigate these negative effects, as the remaining plant cover slows down water flow, promoting its gradual infiltration into deeper soil layers. This process also contributes to moisture accumulation, ensuring better water availability for future vegetation (Drobitko et al., 2023).

Moreover, the preservation of plant residues promotes the activation of biological processes in the soil, as organic matter serves as a food source for microorganisms and earthworms, which improve soil structure, enhance its water permeability, and contribute to the formation of stable aggregates. As a result, the soil surface becomes less prone to degradation under external influences, allowing for more effective control of water and wind erosion (Aliyev et al., 2021).

The issue of erosion control has become particularly relevant in the context of global climate change, as the increasing frequency of extreme weather events – such as heavy rainfall, droughts, and hurricane-force winds – significantly complicates agricultural practices. Under these conditions, the implementation of conservation tillage, the preservation of natural vegetation cover, the rational use of mulching, and adaptive tillage systems have become essential for maintaining the stable productivity of agroecosystems (Tsoraeva et al., 2021);

d) soil fertility preservation. This is a key objective of modern agriculture, playing a crucial role in ensuring stable crop yields and maintaining the ecological balance of agroecosystems. Achieving this goal is possible through the implementation of minimum tillage, which helps reduce the intensity of mineralization processes, prevents humus loss, and promotes the accumulation of organic matter. One of the essential elements of this technology is the retention of plant residues from previous crops in the field, which serve as an alternative source of organic matter replenishment in the soil and create favorable conditions for activating biological processes (Jiang et al., 2024).

Organic residues play a crucial role in maintaining the natural plant nutrition cycle, as they serve as the primary substrate for soil microorganisms that decompose plant matter and enrich the soil with essential nutrients. This process enhances microbiological activity, increases the efficiency of nitrogen-fixing bacteria, and promotes the development of beneficial microflora, facilitating the transformation of organic matter into plant-available nutrient forms. Additionally, organic residues contribute to the formation of a stable soil structure, improving moisture retention capacity and water permeability, which is particularly important in arid climates (Gao et al., 2023).

Minimum tillage, combined with agronomic practices aimed at preserving the soil's natural structure, supports the gradual restoration of the fertile layer. This approach encourages natural soil formation, restores the organic matter balance, reduces environmental impact, and creates more favorable conditions for crop cultivation. Furthermore, this method helps mitigate erosion, as an undisturbed soil layer with abundant organic residues is more resistant to wind and water erosion, minimizing fertile soil losses and preserving its productive properties (Jiang et al., 2024).

e) weed, pest, and disease control. This is one of the most critical tasks of modern soil tillage, as the phytosanitary status largely determines crop yield levels and agricultural product quality. In recent decades, there has been an uncontrolled increase in weed infestation in arable land. The topsoil accumulates a massive amount of vegetative weed propagules, reaching 150,000–300,000 shoots per hectare, along with a seed bank ranging 0.5 to 1.0 billion seeds per hectare. This situation complicates effective agricultural production and increases the need for improved methods of weed control (Rawat et al., 2021).

Moreover, widespread weed growth creates a favorable environment for the reproduction and spread of pests and pathogenic microorganisms, which negatively affect crop development, reduce their competitiveness, and make agriculture more dependent on intensive protection measures. Harmful organisms that use weeds as shelter and a food source can rapidly adapt to unfavorable conditions and pose a significant threat to crops, leading to substantial economic losses in the agricultural sector. A particularly alarming trend is the gradual increase in populations of quarantine and highly aggressive weed species, which – due to their high viability, rapid reproduction, and resistance to control methods – outcompete cultivated plants and cause severe soil depletion (Abbas et al., 2022).

The high population density and widespread distribution of harmful organisms in agroecosystems have increased the need for integrated plant protection systems, which include mechanical, chemical, and biological control methods. Modern soil tillage approaches emphasize rational technologies that not only eliminate weeds during the early vegetative stages but also minimize favorable conditions for their further spread. One such method is reduced tillage, which disrupts the biological cycle of many weed species, particularly those that propagate by seed, and limits their viability by creating a dense plant residue cover (Riemens et al., 2022).

At the same time, modern tillage technologies help reduce the habitat range of pests and disease-causing pathogens, as they alter the soil microclimate, making it less favorable for pathogenic organisms. The use of crop rotation and mulch tillage enhances the effectiveness of weed control, since certain crops can naturally suppress the growth and development of unwanted vegetation, thereby reducing soil strain (Costa et al., 2023).

f) creating optimal agrophysical soil conditions (density, hardness, porosity, and aeration). The formation of optimal agrophysical characteristics of the soil is one of the most crucial aspects of modern agriculture, as the physical state of the soil directly affects crop growth, development, and productivity. Soil density, hardness, porosity, and aeration determine not only the ease of seed germination and root system formation but also the ability of plants to efficiently utilize moisture and nutrients. Overcompacted soil creates mechanical barriers that restrict root penetration into deeper horizons, reduce oxygen availability, and slow down water absorption, leading to a significant decline in overall plant health. On the other hand, overly loose or weakly structured soil is also problematic, as it accelerates moisture evaporation, increases the risk of nutrient leaching, and can lead to degradation processes such as erosion and deflation (Gaevaya et al., 2022).

Optimizing the physical parameters of the soil is essential for creating a favorable environment for the development of the root system of field crops. An adequate level of porosity helps maintain a balance between the soil's water and air phases, improving oxygen availability for the plant roots and stimulating the activity of soil microorganisms involved in organic matter decomposition and nutrient mineralization. At the same time, controlled soil hardness ensures structural stability, reducing the risk of compaction under mechanical pressure and promoting the even distribution of moisture throughout the soil profile. Aeration, as one of the most critical factors, facilitates intensive gas exchange within the soil, supporting oxidation-reduction processes, maintaining biological activity, and preserving the natural fertility of the soil environment (Sattarovich et al., 2023).

Ensuring optimal agrophysical soil conditions requires the use of rational tillage technologies that consider the biological characteristics of cultivated crops, their moisture and aeration requirements, as well as the climatic and soil conditions of the region. For example, crops with robust root systems, such as corn and sunflower, require well-loosened soil with high water permeability, while cereal crops thrive better in moderately compacted soils, which ensure uniform moisture distribution. The use of combined tillage implements, minimum or strip tillage technologies, green manure crops (cover crops), and organic fertilizers helps preserve the optimal soil structure, enhances natural fertility, improves the conditions for the development of root system, and ultimately ensures stable increases in agricultural crop yields (Ivanov et al., 2021);

g) creating favorable conditions for seed sowing. Favorable conditions for seed sowing in field crops are essential for ensuring uniform and high-quality plant growth, as this directly influences yield quantity and quality. One of the key steps is field surface leveling, which allows for even water distribution, improves moisture infiltration into the soil, and ensures consistent sowing depth. This process is essential for both uniform moisture availability and the efficient operation of agricultural machinery in later fieldwork stages. Soil loosening is another vital element, as it helps create optimal conditions for seed germination, enhances soil aeration, and stimulates the development of root system, allowing plants to efficiently absorb water and nutrients. Additionally, loosening aids in preserving soil structure, reducing the risk of compaction, which is often a problem after the use of heavy machinery (Johnson et al., 2021).

Weed elimination is a critical step in seedbed preparation, as competition for resources such as water, nutrients, and sunlight can significantly reduce crop yield. The use of chemical and mechanical methods of weed control effectively reduces weed populations within the agroecosystem, creating optimal conditions for further crop growth and development. Rolling the field after sowing is another important step in creating optimal conditions for the seedlings, as rollers compact the soil around the seeds, improving seed-to-soil contact and promoting even germination. This stage is particularly important in low-moisture conditions, as it helps retain moisture in the topsoil, which is crucial for successful seed germination (Jarrar et al., 2023).

In case of no-till technology, seedbed preparation occurs without traditional loosening or plowing, preserving the structure of the topsoil, reducing erosion, and minimizing moisture loss. No-till farming involves direct seeding into untilled soil, which lowers tillage costs but requires the use of specialized agricultural machinery capable of precisely controlling sowing depth and density. At the same time, mechanical or chemical weed control before or after sowing is essential to minimize weed competition with crops. This approach helps retain soil moisture, reduce organic matter loss, and maintain soil structure, ultimately ensuring high crop productivity. All these steps contribute to creating optimal conditions for plant growth and development, leading to healthy seedlings, high yields, and stable agricultural production (Soto-Gómez et al., 2022).

Development and implementation of modern soil tillage technologies in Ukraine

The development of Ukraine's agricultural sector amid climate change, rising costs for fuel and lubricants, and the need to increase land use efficiency is driving a shift away from traditional soil tillage approaches (Dzhabborov et al., 2021; Naorem et al., 2023).

In recent years, there has been a widespread adoption of energy-efficient, soil-conserving, and resource-saving technologies, which contribute to moisture conservation, soil fertility enhancement, and cost optimization in agricultural crop production (Klima et al., 2019):

a) variable-rate tillage technologies. The variable-rate tillage approach is a cornerstone of modern agricultural technologies, promoting soil conservation, productivity enhancement, and efficient resource utilization, ultimately ensuring the sustainable development of agricultural production.

Modern agricultural technologies are based on the concept of rational and adaptive tillage, which considers soil physicochemical properties, degradation levels, erosion processes, and nutrient availability. The differentiated approach enables the optimization of technological operations, improvement of soil fertility, and reduction of production costs for agricultural crops.

For highly eroded soils, particularly on sloped lands, deep chisel (conservation) tillage technologies are applied using chisel plows and chisel cultivators or minimum tillage systems such as no-till or strip-till. These methods help retain moisture, reduce runoff and wind erosion, and increase soil resistance to degradation processes. Additionally, mulching and crop residue management further protect the soil from mechanical degradation and contribute to the accumulation of organic matter, enhancing soil structure and long-term fertility.

On moderately degraded and insufficiently cultivated soils, the mini-till system is often applied, allowing for partial preservation of the natural soil structure while simultaneously improving aeration and water permeability. The use of disc or sweep implements for shallow loosening promotes even distribution of nutrients and creates favorable conditions for the growth of root system.

For fertile soils with high humus content, good structure, and water permeability, traditional moldboard tillage can be applied, particularly for deep-rooted crops such as sunflower and corn, which require a loose soil environment for optimal development. However, due to its high energy consumption and the risk of soil structure degradation, this approach is used to a limited extent, mainly on heavy-textured soils where reducing soil density is necessary.

Balanced plant nutrition is of particular importance and is achieved through precise analysis of soil composition and variable-rate fertilizer application. The use of precision agriculture technologies allows for the adjustment of macro- and micronutrient levels based on the specific needs of different field areas, improving fertilization efficiency while reducing environmental impact.

Deep loosening with chisel implements instead of traditional plowing helps reduce compaction of soil and preserve its structure. Chisel (conservation) tillage is one of the methods of minimum tillage, involving loosening without inverting the soil layer. It is performed using chisel plows, which penetrate 20 to 40 cm deep, enhancing water infiltration and air exchange. Additionally, a significant portion of plant residues remains on the surface, helping retain moisture and prevent water and wind erosion (Salar et al., 2021).

One of the main advantages of chisel tillage is its ability to improve soil structure without disrupting its natural profile. This method helps preserve the humus layer, slow down the mineralization of organic matter, and create favorable conditions for the development of root system and activity of soil microbial. Additionally, chisel tillage contributes to fuel savings, as it requires less energy consumption than traditional plowing.

However, chisel tillage also has certain disadvantages. One issue is the accumulation of plant residues on the surface, which can slow down their decomposition and create challenges for crop growth. Additionally, since soil inversion does not occur, there is an increased risk of perennial weed proliferation, necessitating effective control measures, such as herbicide application or mechanical removal. In spring, chisel-tilled fields may warm up more slowly, which can sometimes affect the sowing schedule for heat-loving crops.

Chisel tillage is widely used in minimum tillage systems, particularly in arid regions such as the Ukrainian Steppe. Its application significantly preserves soil moisture, enhances soil fertility, and promotes stable crop yields. For this reason, chisel tillage is an essential component of modern environmentally oriented farming (Bibutov et al., 2021).

Localized application of fertilizer combined with soil tillage is an effective agronomic practice that ensures optimal availability of nutrients for crops and efficient use of fertilizers. This approach helps minimize nutrient losses, reduce their fixation in the soil, and create better conditions for the growth and development of crop root systems (Kaminskyi et al., 2022).

Applying fertilizers directly in the zone where roots actively absorb nutrients increases the efficiency of nutrient uptake by crops through their direct delivery to the soil layers where the majority of roots are concentrated. This is especially important under arid conditions, where the root system primarily develops in the upper soil layers and nitrogen losses due to evaporation or leaching can be significant. The choice of localized application method depends on soil type, nutrient availability, previous crop, and cultivation technology (Turganbayev et al., 2023).

The most common methods include band application in the seeding layer, deep fertilizer placement using specialized applicators, or a combination with pre-sowing cultivation. Integrating localized fertilization with soil tillage not only ensures a uniform nutrient distribution within the plow layer but also creates optimal conditions for the development root system. This approach enhances soil aeration, water retention capacity, and capillary moisture movement, supporting healthy crop growth (Maliarchuk et al., 2021; Turganbayev et al., 2023).

When fertilizers are applied simultaneously with primary or pre-sowing tillage, they are evenly incorporated into the soil, ensuring the gradual release of nutrients and their availability throughout the growing season. Localized placement of nitrogen fertilizer reduces nitrate nitrogen losses, which is especially important for light sandy and loamy soils prone to leaching.

At the same time, the direct application of phosphorus and potassium fertilizers in the root zone increases their utilization efficiency, as these nutrients are less mobile in the soil and require direct contact with the root system for effective uptake. The choice of a specific localized fertilization method, combined with soil tillage, should be based on soil agrochemical analysis, the physicochemical properties of fertilizers, and the biological characteristics of the cultivated crop (Bryant et al., 2021; Fen et al., 2021; Zhang et al., 2023);

b) mulch tillage technologies. Mulch tillage is an agronomic practice that involves loosening the soil without inverting the plow layer, while leaving crop residues from previous crops on the soil surface. This approach helps retain moisture, prevent erosion, and improve conditions for plant growth (Lei et al., 2021; Zhang et al., 2022).

The crop residues left on the field serve as mulch, which protects the soil from overheating, regulates thermal properties, and reduces moisture evaporation. Dark mulch absorbs solar radiation, promoting faster soil warming in spring, while light-colored mulch reflects sunlight, preventing overheating in summer (Qin et al., 2024).

Additionally, mulch tillage improves the physical condition of the soil, increases microbiological activity, and contributes to the accumulation of organic matter. The plant residues covering the soil protect it from overheating during dry periods, which is particularly important for moisture conservation and maintaining optimal conditions for plant growth (Buesa et al., 2021; Li et al., 2021; Du et al., 2022).

Mulch tillage enhances crop productivity and profitability, promotes sustainable agricultural practices, preserves chernozem fertility, and regulates the balance of soil, water, air, and nutrients (Ramadhan, 2021).

Mulch tillage is an effective method for enhancing soil fertility and ensuring stable crop yields, particularly in arid climates (Tian et al., 2020; Wang et al., 2023; Wu et al., 2023).

c) minimal and no-till tillage technologies (no-till, mini-till, strip-till). One of the key trends in modern farming systems is the reduction of intensity of mechanical soil tillage. This shift is driven by the need to reduce soil degradation, preserve organic matter, decrease erosion processes, enhance soil fertility, and optimize agricultural production costs. Excessive mechanical tillage can lead to the destruction of soil structure, depletion of humus content, decline of beneficial microbial communities, and deterioration of soil's water and physical properties. Therefore, modern tillage technologies focus on minimizing soil profile disturbance and adopting alternative cultivation approaches (Wulanningtyas et al., 2021).

One of the most radical reduced tillage systems is the no-till technology, which completely eliminates mechanical soil cultivation. In this system, seeding is performed directly into the stubble of the previous crop using specialized seed drills that create narrow slits for seed placement. This method preserves soil structure, while the surface remains covered with plant residues, providing protective benefits, such as reducing moisture evaporation and preventing water and wind erosion (Silva et al., 2023).

Weed control in the no-till system is primarily carried out through chemical methods, using broad-spectrum and selective herbicides. This approach effectively eliminates weeds without mechanical loosening, but it requires careful selection of herbicides and adherence to application guidelines to prevent negative environmental impacts. Plant nutrition in this system relies on the application of mineral fertilizers and the use of cover crops (green manure), which gradually decompose, enriching the soil with essential nutrients (Qi et al., 2022).

The no-till system is particularly effective in the Steppe and Forest-Steppe regions of Ukraine, where it reduces the risk of moisture loss, which is critical during summer droughts. Crop residues left on the soil surface help retain moisture, regulate soil temperature, and protect against extreme fluctuations. Additionally, this technology promotes the gradual increase of organic matter in the soil, enhancing fertility and biological activity (Fuentes-Llanillo et al., 2021).

However, the implementation of no-till requires adaptation of the entire agronomic system, including proper planning of crop rotation and effective management of weeds and pests. A crucial aspect of this system is the use of specialized direct-seeding drills, which allow sowing without disturbing the soil surface layer (Qi et al., 2022).

Thus, no-till is one of the most promising technologies in modern agriculture, as it significantly reduces energy costs, improves soil water balance, enhances erosion resistance, and helps maintain agroecosystem productivity over the long term (Roozbeh et al., 2021).

Mini-till is a minimal tillage system that involves limited mechanical soil disturbance to a depth of 10–12 cm, using disc harrows and sweep cultivators. The primary goal of this technology is to preserve soil fertility by minimizing mechanical loosening, which helps reduce erosion processes, retain moisture, and increase organic matter content.

Unlike traditional moldboard plowing, mini-till provides a gentler intervention in the soil cover, helping to maintain its natural structure. The use of disc harrows or sweep cultivators allows for the partial processing of soil at the surface, while deeper layers remain undisturbed. This approach reduces soil compaction and improves the soil's water-air balance, which has a positive effect on seed germination and root system development in agricultural crops.

One of the key benefits of mini-till is its ability to reduce the risk of wind and water erosion, as some crop residues remain on the soil surface, providing a protective cover. This residue helps retain moisture, decreases evaporation, prevents overheating in summer, and protects against excessive cooling in colder periods. As a result, optimal conditions are created for beneficial soil microorganisms, which facilitate the natural decomposition of organic matter and improve nutrient availability for plants (Volkov et al., 2021).

The mini-till technology also helps reduce fuel costs and equipment wear, as its shallower tillage depth requires less energy compared to traditional plowing. The lower mechanical load on machinery extends its operational lifespan and improves fieldwork efficiency by allowing faster equipment passes. This is particularly crucial during time-sensitive periods such as sowing and harvesting.

Additionally, mini-till helps retain a significant amount of organic matter in the soil, as crop residues are evenly distributed across the surface. This contributes to an increase in humus content and enhances the soil's physicochemical properties. However, reduced tillage intensity creates favorable conditions for the germination of certain weed species, necessitating effective weed control measures. The mini-till system relies on a combination of herbicide application and mechanical weed management, such as sweep cultivators for undercutting weeds.

Thanks to its versatility, mini-till is an effective technology across various agro-climatic zones, particularly in the Steppe and Forest-Steppe regions of Ukraine, where moisture conservation is a priority. It can be used in crop rotations involving a wide range of crops, including cereals, legumes, and industrial crops (Milyutkin et al., 2021). Thus, mini-till serves as an intermediate system between traditional tillage and no-till, combining the advantages of both approaches. It enables cost reduction, soil fertility preservation, erosion prevention, water balance improvement, and supports the transition to sustainable agriculture.

Strip-till is a tillage system that involves loosening and cultivating only the soil strips where crops will be sown, while the inter-row areas remain undisturbed. This approach combines the benefits of traditional tillage and no-till, allowing for reduced soil disturbance, preservation of natural soil structure and moisture, and lower risks of soil degradation (Maliarchuk et al., 2021; Różewicz et al., 2022).

One of the key advantages of strip-till is the ability to apply fertilizers directly into the cultivated strips, improving nutrient uptake by the root system and enhancing crop productivity. Additionally, partial soil loosening in the seed zones ensures better seed-to-soil contact, leading to uniform germination and strong early plant development (Górski et al., 2022; Wang et al., 2023).

The retention of crop residues in the inter-row areas plays a critical protective role – these residues reduce moisture evaporation, protect the soil from overheating in summer, and prevent nutrient leaching during excessive rainfall. Moreover, they act as a source of organic matter, enhancing biological soil activity and promoting the gradual accumulation of humus (Sha et al., 2024).

Another significant benefit of strip-till is its lower energy consumption compared with conventional tillage. Since only 30–40% of the field area is tilled, fuel use is reduced, machinery wear is minimized, and resource efficiency is improved. This makes strip-till particularly suitable for low-moisture regions, such as Ukraine's Steppe (Sereda et al., 2021).

However, the successful implementation of strip-till requires precise adherence to technological parameters, particularly proper alignment of tilled strips with future planting rows. This necessitates the use of modern machinery equipped with precision farming systems, which may require a significant investment from farmers. Additionally, on heavy, compacted soils, extra loosening may be required, partially offsetting the economic benefits of the system. Due to its effectiveness, strip-till is widely used for row crops, such as corn, sunflower, soybean, and rapeseed. This technology improves crop yields by optimizing the growth conditions, while minimizing environmental impact (Kulyk et al., 2020; Lee et al., 2021).

Thus, strip-till represents a promising alternative to traditional plowing and no-till, offering an optimal balance of soil resource management, fertility preservation, and economic feasibility.

Automation and precision agriculture

Automation and precision agriculture are modern approaches in the agricultural sector that enhance soil cultivation efficiency and optimize resource use. The application of advanced monitoring and soil analysis technologies enables farmers to make informed decisions regarding crop management and field maintenance.

Precision agriculture involves the use of modern information technologies to maximize profit, optimize agricultural production, and utilize natural resources efficiently (Raj et al., 2022).

Through the automation of processes such as parallel guidance, soil analysis, and crop monitoring, farmers can reduce costs related to fuel, seeds, and fertilizers, while also increasing crop yields.

The integration of artificial intelligence in precision agriculture allows for real-time monitoring of crop growth, soil conditions, and weather patterns, contributing to effective resource management and waste reduction (Ghazal et al., 2024).

The integration of modern monitoring and soil analysis technologies into precision agriculture enhances the efficiency of agricultural production, reduces costs, and ensures the sustainable development of agroecosystems (Vinod et al., 2024).

Drones and satellite monitoring. Drones and satellite monitoring enable the assessment of soil moisture levels, erosion risks, and fertilization needs. They play a key role in modern agriculture, providing accurate and real-time evaluation of soil and crop conditions. These technologies allow farmers to effectively manage resources and improve crop yields.

Soil moisture assessment. Using satellite imagery and drones, it is possible to monitor crop conditions, soil moisture levels, and overall plant development efficiently (Miller et al., 2024).

Erosion level assessment. Satellite monitoring helps analyze terrain conditions, evaluate soil fertility levels, and track weather patterns (Zhang et al., 2024).

Fertilization needs assessment. Drone monitoring is an effective tool for controlling uniformity of fertilizer distribution, detecting plant diseases and pests at early development stages, and optimizing irrigation based on the specific needs of each field segment.

The integration of drones and satellite monitoring into agricultural processes enhances farm management efficiency, reduces costs, and ensures the sustainable development of agriculture (Raoufat et al., 2020).

Navigation through GPS and precision agriculture systems optimize agricultural processes by enabling accurate control of machinery movement, which helps minimize overlaps in treated areas, reducing fuel consumption, equipment wear, and unnecessary resource expenditures. As a result, the efficiency of agricultural machinery increases, while fuel, fertilizer, and pesticide costs decrease, positively affecting farm economics and promoting the rational use of natural resources (Padhiary et al., 2024).

Additionally, articulated robots and automated systems allow for the precise application of fertilizers and plant protection products, preventing overuse, reducing negative environmental impacts on soil and ecosystems, and ensuring the even distribution of nutrients, which enhances crop quality and yield.

The use of such technologies reduces manual labor, increases productivity, and automates soil management processes, leading to the development of more sustainable and efficient agroecosystems (Gorjian et al., 2020; Kitić et al., 2022; Azmi et al., 2023).

Conclusion

Modern trends in soil tillage worldwide and in Ukraine are focused on reducing energy consumption, preserving soil fertility, and adapting to climate change. Amidst global warming, characterized by prolonged droughts and severe weather events, there is an urgent call to enhance agricultural technologies that maintain consistent productivity while reducing the harmful effects of human actions on the environment.

One of the key directions is the wider adoption of minimal and no-till systems, which help reduce soil erosion, improve soil structure, retain moisture, and decrease carbon dioxide emissions into the atmosphere. The use of cover crops and mulching plays a crucial role in restoring soil fertility, as they contribute to the accumulation of organic matter, improvement of water balance, reduction in the need for mineral fertilizers, and protection of soil from degradation.

The implementation of precision agriculture, based on satellite navigation systems, drones, sensors, and geographic information systems (GIS), significantly enhances soil cultivation efficiency. These technologies allow for precise calculation of fertilizer and pesticide application rates, minimizing their excessive impact on ecosystems, and optimizing fuel consumption by preventing overlaps during field treatments.

Innovative agricultural technologies, such as automated control systems for agricultural machinery, autonomous tractors, robotic soil cultivation systems, and AI-driven data analysis, reduce labor costs and improve the quality of field operations. The use of biological plant protection methods and microbial-based products further helps reduce chemical stress on the soil and preserve its biological diversity.

In the future, digital technologies and process automation are expected to be actively integrated into agriculture, making soil tillage even more efficient and environmentally sustainable. Artificial intelligence (AI) and machine learning will enable farmers to receive more accurate predictions regarding soil conditions, optimal timing for agricultural operations, and yield forecasts. Satellite monitoring and blockchain systems will ensure transparency in agricultural processes and enhance food security.

Overall, the future of soil tillage is closely linked to the expansion of sustainable farming practices, which maintain a balance between productivity, economic efficiency, and natural resource conservation. The integrated use of precision agriculture technologies, innovative agricultural technological solutions, and biological farming methods will contribute to soil preservation for future generations, while enhancing productivity in the face of climate change.

References

Abbas, M., Saleem, M., Hussain, D., Ramzan, M., Jawad Saleem, M., Abbas, S., & Parveen, Z. (2022). Review on integrated disease and pest management of field crops. International Journal of Tropical Insect Science, 42(5), 3235–3243.

Akhter, R., & Sofi, S. A. (2022). Precision agriculture using IoT data analytics and machine learning. Journal of King Saud University-Computer and Information Sciences, 34(8), 5602–5618.

Aliyev, Z. H. (2021). The effectiveness of the application of comprehensive measures to combat erosion using irrigation in a market economy in Azerbaijan. Journal of Emerging Trends in Economics and Management Sciences, 12(2), 79–84.

Azmi, H. N., Hajjaj, S. S. H., Gsangaya, K. R., Sultan, M. T. H., Mail, M. F., & Hua, L. S. (2023). Design and fabrication of an agricultural robot for crop seeding. Materials Today: Proceedings, 81, 283–289.

Bibutov, N. (2021). Parameters of deep chiseling of soil. IOP Conference Series: Earth and Environmental Science, 839(5), 052037.

Bryant, C. J., Locke, M. A., Krutz, L. J., Reynolds, D. B., Golden, B. R., Irby, T., ... & Spencer, G. D. (2021). Furrow-irrigation application efficiency in mid-southern US conservation tillage systems. Agronomy Journal, 113(1), 397–406.

Buesa, I., Mirás-Avalos, J. M., De Paz, J. M., Visconti, F., Sanz, F., Yeves, A., & Intrigliolo, D. S. (2021). Soil management in semi-arid vineyards: Combined effects of organic mulching and no-tillage under different water regimes. European Journal of Agronomy, 123, 126198.

Caputo, S. (2022). History, techniques and technologies of soil-less cultivation. In: Caputo, S. (Ed.). Small scale soil-less urban agriculture in Europe. Springer, Cham. Pp. 45–86.

Costa, C. A., Guiné, R. P., Costa, D. V., Correia, H. E., & Nave, A. (2023). Pest control in organic farming. In: Chen, J., & Chang, C. (Eds.). Advances in resting-state functional MRI. Methods, interpretation, and applications. Academic Press. Pp. 111–179.

Drobitko, A., Markova, N., Tarabrina, A. M., & Tereshchenko, A. (2023). Land degradation in Ukraine: Retrospective analysis 2017–2022. International Journal of Environmental Studies, 80(2), 355–362.

Du, C., Li, L., & Effah, Z. (2022). Effects of straw mulching and reduced tillage on crop production and environment: A review. Water, 14(16), 2471.

Dzhabborov, N. I., Dobrinov, A. V., & Semenova, G. A. (2021). Evaluation of the ecological efficiency of soil cultivation machines with innovative dynamic working bodies. E3S Web of Conferences, 262, 04008.

El-Beltagi, H. S., Basit, A., Mohamed, H. I., Ali, I., Ullah, S., Kamel, E. A., & Ghazzawy, H. S. (2022). Mulching as a sustainable water and soil saving practice in agriculture: A review. Agronomy, 12(8), 1881.

Fan, D., Jia, G., Wang, Y., & Yu, X. (2023). The effectiveness of mulching practices on water erosion control: A global meta-analysis. Geoderma, 438, 116643.

Fen, W. U., Zhai, L. C., Ping, X. U., Zhang, Z. B., Baillo, E. H., Tolosa, L. N., ... & Guo, H. Q. (2021). Effects of deep vertical rotary tillage on the grain yield and resource use efficiency of winter wheat in the Huang-Huai-Hai Plain of China. Journal of Integrative Agriculture, 20(2), 593–605.

Fuentes-Llanillo, R., Telles, T. S., Junior, D. S., de Melo, T. R., Friedrich, T., & Kassam, A. (2021). Expansion of no-tillage practice in conservation agriculture in Brazil. Soil and Tillage Research, 208, 104877.

Fussy, A., & Papenbrock, J. (2022). An overview of soil and soilless cultivation techniques-chances, challenges and the neglected question of sustainability. Plants, 11(9), 1153.

Gaevaya, E. A., Bezuglova, O. S., & Nezhinskaya, E. N. (2022). Agrophysical properties of ordinary slightly eroded chernozem in a long-term experiment in Rostov Oblast. Eurasian Soil Science, 55(11), 1609–1622.

Gavrilescu, M. (2021). Water, soil, and plants interactions in a threatened environment. Water, 13(19), 2746.

Ghazal, S., Munir, A., & Qureshi, W. S. (2024). Computer vision in smart agriculture and precision farming: Techniques and applications. Artificial Intelligence in Agriculture, 13, 64–83.

Gorjian, S., Minaei, S., Maleh Mirchegini, L., Trommsdorff, M., & Shamshiri, R. R. (2020). Applications of solar PV systems in agricultural automation and robotics. In: Gorjian, S., & Shukla, A. (Eds.). Photovoltaic solar energy conversion. Technologies, applications and environmental impacts. Academic Press. Pp. 191–235.

Górski, D., Gaj, R., Ulatowska, A., & Miziniak, W. (2022). Effect of strip-till and variety on yield and quality of sugar beet against conventional tillage. Agriculture, 12(2), 166.

Ivanov, A. I., & Ivanova, Z. A. (2021). Methodology of the Agrophysical Institute's modern system of field experiments. In: Mueller, L., Sychev, V. G., Dronin, N. M., & Eulenstein, F. (Eds.). Exploring and optimizing agricultural landscapes. Springer, Cham. Pp. 529–546.

Jarrar, H., El-Keblawy, A., Ghenai, C., Abhilash, P. C., Bundela, A. K., Abideen, Z., & Sheteiwy, M. S. (2023). Seed enhancement technologies for sustainable dryland restoration: Coating and scarification. Science of the Total Environment, 904, 166150.

Jiang, F., Xue, X., Zhang, L., Zuo, Y., Zhang, H., Zheng, W., & Peng, X. (2024). Soil wind erosion, nutrients, and crop yield response to conservation tillage in North China: A field study in a semi-arid and wind erosion region after 9 years. Field Crops Research, 316, 109508.

Johnson, R., & Puthur, J. T. (2021). Seed priming as a cost effective technique for developing plants with cross tolerance to salinity stress. Plant Physiology and Biochemistry, 162, 247–257.

Kaminskyi, V., Bulgakov, V., Tkachenko, M., Kolomiiets, M., Kaminska, V., Ptashnik, M., & Kiernicki, Z. (2022). Research into comparative performance of different tillage and fertilization systems applied to Grey Forest Soil of forest steppe in grain crop rotation. Journal of Ecological Engineering, 23(12), 163–178.

Kitić, G., Krklješ, D., Panić, M., Petes, C., Birgermajer, S., & Crnojević, V. (2022). Agrobot Lala – an autonomous robotic system for real-time, in-field soil sampling, and analysis of nitrates. Sensors, 22(11), 4207.

Klima, K., Lepiarczyk, A., Chowaniak, M., & Boligłowa, E. (2019). Soil protective efficiency of organic cultivation of cereals. Journal of Elementology, 24(1), 357–368.

Kulyk, M., Kalinichenko, O., & Dekovetz, V. (2020). Efficiency of energy crops cultivation for business development in Ukraine. In: Nestorenko, T., & Pokusa, T. (Eds.). Organization and management in the services' sphere on selected examples. The Academy of Management and Administration in Opole, Opole. Pp. 36–45.

Kumar, P., Chugh, P., Ali, S. S., Chawla, W., Sushmita, S., Kumar, R., ... & Kumar, R. (2024). Trends of nanobiosensors in modern agriculture systems. Applied Biochemistry and Biotechnology, 197, 667–690.

Lee, H., Sam, K., Coulon, F., De Gisi, S., Notarnicola, M., & Labianca, C. (2024). Recent developments and prospects of sustainable remediation treatments for major contaminants in soil: A review. Science of the Total Environment, 912, 168769.

Lei, E., Wang, C., Li, W. X., Wang, Y. D., Yang, Y. B., Zheng, H. B., & Tang, Q. Y. (2021). Straw mulching with minimum tillage is the best method suitable for straw application under mechanical grain harvesting. Scientific Programming, 2021, 6878176.

Li, Y. M., Duan, Y., Wang, G. L., Wang, A. Q., Shao, G. Z., Meng, X. H., ... & Zhang, D. M. (2021). Straw alters the soil organic carbon composition and microbial community under different tillage practices in a meadow soil in Northeast China. Soil and Tillage Research, 208, 104879.

Lv, L., Gao, Z., Liao, K., Zhu, Q., & Zhu, J. (2023). Impact of conservation tillage on the distribution of soil nutrients with depth. Soil and Tillage Research, 225, 105527.

Lykhovyd, P. (2021). Irrigation needs in Ukraine according to current aridity level. Journal of Ecological Engineering, 22(8), 11–18.

Majeed, Y., Khan, M. U., Waseem, M., Zahid, U., Mahmood, F., Majeed, F., ... & Raza, A. (2023). Renewable energy as an alternative source for energy management in agriculture. Energy Reports, 10, 344–359.

Maliarchuk, M., Maliarchuk, A., Tomnytskyi, A., Maliarchuk, V., & Lykhovyd, P. (2021). Influence of basic tillage systems and fertilization on productivity and economic efficiency of irrigated crop rotation. Agricultural Systems, 21(4), 345–353.

Manlay, R. J., Feller, C., & Swift, M. J. (2022). Historical evolution of soil organic matter concepts and their relationships with the fertility and sustainability of cropping systems. Agriculture, Ecosystems and Environment, 119(3–4), 217–233.

Meyer, M., Diehl, D., Schaumann, G. E., & Muñoz, K. (2021). Multiannual soil mulching in agriculture: Analysis of biogeochemical soil processes under plastic and straw mulches in a 3-year field study in strawberry cultivation. Journal of Soils and Sediments, 21, 3733–3752.

Miller, J. O., Mondal, P., & Sarupria, M. (2024). Sensor-based measurements of NDVI in small grain and corn fields by tractor, drone, and satellite platforms. Crop and Environment, 3(1), 33–42.

Milyutkin, V., Buxmann, V., Meskhi, B., Rudoy, D., & Olshevskaya, A. (2021). Innovative complex for in-soil fertilizer X Tender + Cenius for Mini-Till technology. In: XIV International Scientific Conference "Interagromash 2021". Precision agriculture and agricultural machinery industry. Vol. 1. Pp. 122–129.

Naorem, A., Jayaraman, S., Dang, Y. P., Dalal, R. C., Sinha, N. K., Rao, C. S., & Patra, A. K. (2023). Soil constraints in an arid environment – challenges, prospects, and implications. Agronomy, 13(1), 220.

Padhiary, M., Kumar, R., & Sethi, L. N. (2024). Navigating the future of agriculture: A comprehensive review of automatic all-terrain vehicles in precision farming. Journal of the Institution of Engineers: Series A, 105, 767–782.

Qi, J. Y., Han, S. W., Lin, B. J., Xiao, X. P., Jensen, J. L., Munkholm, L. J., & Zhang, H. L. (2022). Improved soil structural stability under no-tillage is related to increased soil carbon in rice paddies: Evidence from literature review and field experiment. Environmental Technology and Innovation, 26, 102248.

Qin, W., Niu, L., You, Y., Cui, S., Chen, C., & Li, Z. (2024). Effects of conservation tillage and straw mulching on crop yield, water use efficiency, carbon sequestration and economic benefits in the Loess Plateau region of China: A meta-analysis. Soil and Tillage Research, 238, 106025.

Raj, E. F. I., Appadurai, M., & Athiappan, K. (2022). Precision farming in modern agriculture. In: Choudhury, A., Biswas, A., Singh, T. P., & Ghosh, S. K. (Eds.). Smart agriculture automation using advanced technologies: Data analytics and machine learning, cloud architecture, automation and IoT. Springer, Singapore. Pp. 61–87.

Ramadhan, M. N. (2021). Yield and yield components of maize and soil physical properties as affected by tillage practices and organic mulching. Saudi Journal of Biological Sciences, 28(12), 7152–7159.

Raoufat, M. H., Dehghani, M., Abdolabbas, J., Kazemeini, S. A., & Nazemossadat, M. J. (2020). Feasibility of satellite and drone images for monitoring soil residue cover. Journal of the Saudi Society of Agricultural Sciences, 19(1), 56–64.

Rawat, L., Bisht, T. S., & Naithani, D. C. (2021). Plant disease management in organic farming system: Strategies and challenges. In: Singh, K. P., Jahagirdar, S., & Sarma, B. K. (Eds.). Emerging trends in plant pathology. Springer, Singapore. Pp. 611–642.

Riemens, M., Sønderskov, M., Moonen, A. C., Storkey, J., & Kudsk, P. (2022). An integrated weed management framework: A pan-European perspective. European Journal of Agronomy, 133, 126443.

Roozbeh, M., & Rajaie, M. (2021). Effects of residue management and nitrogen fertilizer rates on accumulation of soil residual nitrate and wheat yield under no-tillage system in south-west of Iran. International Soil and Water Conservation Research, 9(1), 116–126.

Różewicz, M. (2022). Review of current knowledge on strip-till cultivation and possibilities of its popularization in Poland. Polish Journal of Agronomy, 49, 20–30.

Salar, M. R., Karparvarfard, S. H., Askari, M., & Kargarpour, H. (2021). Forces and loosening characteristics of a new winged chisel plough. Research in Agricultural Engineering, 67(1), 17–25.

Sattarovich, M. A., & Ogli, U. U. Z. (2023). Agro physical features of gray soils in dry land that are exposed to erosion. Texas Journal of Agriculture and Biological Sciences, 18, 30–31.

Sereda, L. P., & Kovalchuk, D. A. (2021). Mathematical modeling of the soil processing aggregate in the "Ground aggregate-energetic device" system for strip-till soil processing technology. Machinery and Energetics, 12(4), 103–108.

Sha, Y., Huang, Y., Hao, Z., Gao, M., Jiang, J., Hu, W., ... & Mi, G. (2024). Maize yield in a strip-till system can be increased by increasing nitrogen accumulation, plant growth, and ear development around silking stage in Northeast China. The Crop Journal, 13(1), 257–268.

Silva, G. F. D., Calonego, J. C., Luperini, B. C. O., Silveira, V. B., Chamma, L., Soratto, R. P., & Putti, F. F. (2023). No-tillage system can improve soybean grain production more than conventional tillage system. Plants, 12(21), 3762.

Soto-Gómez, D., & Pérez-Rodríguez, P. (2022). Sustainable agriculture through perennial grains: Wheat, rice, maize, and other species. A review. Agriculture, Ecosystems and Environment, 325, 107747.

Tian, P., Lian, H., Wang, Z., Jiang, Y., Li, C., Sui, P., & Qi, H. (2020). Effects of deep and shallow tillage with straw incorporation on soil organic carbon, total nitrogen and enzyme activities in Northeast China. Sustainability, 12(20), 8679.

Tsoraeva, E., Alborova, P., Bazaeva, L., Khanaeva, D., & Kozyrev, B. (2021). Modern innovative and unconventional methods to combat soil erosion. E3S Web of Conferences, 284, 02003.

Tsyliuryk, O. I., Kotchenko, M. V., Horshchar, V. I., Rumbakh, M. Y., Izhboldin, O. O., & Izhboldina, O. O. (2022). Mulch tillage – principle of presservation of chernozem of the northern steppe of Ukraine. Acta Agriculturae Slovenica, 118(4), 1–12.

Turganbayev, N. O., Sydik, D. A., Kenenbayev, S. B., Sydykov, M. A., & Kazybayeva, A. T. (2023). Optimization of winter wheat nutrition with zero tillage technology in the rainfed zones of Southern Kazakhstan. Sabrao Journal of Breeding and Genetics, 55(5), 1593–1603.

Vinod Chandra, S. S., Anand Hareendran, S., & Albaaji, G. F. (2024). Precision farming for sustainability: An agricultural intelligence model. Computers and Electronics in Agriculture, 226, 109386.

Volkov, A. I., & Prokhorova, L. N. (2021). The use of no-till and mini-till on soils of the Volga-Vyatka Region. In: Mueller, L., Sychev, V. G., Dronin, N. M., & Eulenstein, F. (Eds.). Exploring and optimizing agricultural landscapes. Springer, Cham. Pp. 559–571.

Wang, Q., Wang, B., Sun, M., Sun, X., Zhou, W., Tang, H., & Wang, J. (2023). Design and testing of an automatic strip-till machine for conservation tillage of corn. Agronomy, 13(9), 2357.

Wang, Z., Sui, P., Lian, H., Li, Y., Liu, X., Xu, H., ... & Jiang, Y. (2023). Tillage with straw incorporation reduces the optimal nitrogen rate for maize production by affecting crop uptake, utility efficiency, and the soil balance of nitrogen. Land Degradation and Development, 34(10), 2825–2837.

Wu, P., Li, L., & Wang, X. (2023). Shallow plough tillage with straw return increases rice yield by improving nutrient availability and physical properties of compacted subsurface soils. Nutrient Cycling in Agroecosystems, 127(1), 69–83.

Wulanningtyas, H. S., Gong, Y., Li, P., Sakagami, N., Nishiwaki, J., & Komatsuzaki, M. (2021). A cover crop and no-tillage system for enhancing soil health by increasing soil organic matter in soybean cultivation. Soil and Tillage Research, 205, 104749.

Zhang, D., Guo, Y., Fan, Z., Hu, X., Hao, X., Fang, L., & Li, C. (2023). Tradeoffs between grain yields and ecological efficiencies in a wheat–maize cropping system using optimized tillage and fertilization management on the North China Plain. Environmental Science and Pollution Research, 30(9), 24479–24493.

Zhang, W., Yu, Q., Tang, H., Liu, J., & Wu, W. (2024). Conservation tillage mapping and monitoring using remote sensing. Computers and Electronics in Agriculture, 218, 108705.