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Review

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Progressive Technologies in Agriculture Affecting the Quality of Primary Crop Production – a Review

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Agriculture is a key component in the global land, water, air, and energy nexus, and the way agriculture treats land can significantly affect the ecosystems and the environment. Agriculture plays a significant role in climate change, with its effects varying depending on whether the land is conserved or degraded. Through the adoption of alternative agricultural practices, such as regenerative or conservation methods, it is possible not onlyenhance the soil's organic carbon content and restore degraded land but also to contribute positively to climate change mitigation and overall environmental health. The positive impact of alternative agriculture on the quality of primary food raw materials is also proven. This review article aims to summarize scientific information focused on the impact of alternative ways of soil technology in agriculture and to discuss the positives and negatives of preservative technologies such as minimization, mulch-till, and no-till on the soil, plant production, and the environment.

Key words: agriculture, progressive soil technologies, alternative technologies, plant production, quality

Alternatives to Conventional Ways of Agriculture

In recent years, the agricultural system has become increasingly complex and vulnerable. As the global population grows, so does the demand for food, yet essential resources like arable land and water remain limited. The pressure on these finite resources, coupled with the rising demand for food, has primarily − though not exclusively − burdened small-scale farmers (Khatri *et al*. 2023).

The global food system is responsible for about 25% of annual human-caused greenhouse gas emissions. It also results in about a third of soil acidification and is responsible for most of the world's eutrophication of surface waters (Poore & Nemecek 2018). If the food system continues with current practices involving the use of synthetic pesticides, fertilisers, fossil fuels, and the production of large amounts of food waste, the carrying capacity of the planet will be exceeded (Campbell *et al*. 2017). For this reason, the production of safe and nutritionally valuable food for a growing human population within the carrying capacity of the planet is a key challenge (Willett *et al*. 2019; Schreefel *et al*. 2020; Galanakis 2024). The importance of sustainable food production is currently embedded also in many geopolitical strategic issues of the European Union,

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such as the Strategic Dialogue on the Future of EU Agriculture (2024), the European Green Deal (European Commission 2020a) or the EU Mission: Agreement on land for Europe (Europian Union 2021), EU Circular Economy Action Plan (European Commission 2015), the Paris Climate Agreement (UN Climate Change Conference 2015), and the Common Agricultural Policy (European Commission 2019).

Sustainable agricultural practices offer solutions for producing food and other agricultural products with minimal environmental impact, ensuring that food availability and the well-being of future generations are not compromised (Robertson 2015; Schreefel *et al*. 2020; Galanakis 2024). Sustainable agriculture can also be defined as an integrated system of plant and animal production methods designed to meet long-term food demands while enhancing the quality of the environment and the natural resources that support agricultural economies. This system also makes it possible to maintain natural biological cycles, the economic viability of farming activities, and increase the quality of farmers' lives and the whole society (Keeney 1990; Siebrecht 2020). On the other hand, sustainable agriculture depends on the development of advanced approaches (activities, factors) to enhance crop yield and improve other agriculture measures and to make the agriculture wilderness friendly and sustainable (Figure 1).

It is widely acknowledged that as the global population continues to grow, the demand for food rises, leading to the conversion of forests and arable land into urban areas. Considering diminishing arable land, highly efficient and advanced technologies are essential to meet the food demands of an expanding global population (Khan *et al*. 2021). Many of these approaches are defined and comprehensively described in academic literature, for example, organic farming and climate-smart agriculture. An approach that has recently gained attention as a potential solution for a sustainable food system is regenerative agriculture (Rodale 1983; Schreefel *et al*. 2020; Muhie 2022). One of the main principles that unites all the mentioned alternative agricultural methods is the system of sustainable intensification. Climate-Smart Agriculture involves practices that support both agricultural productivity and climate adaptation, which is highly desirable in today's age of recognized climate change and increasing food demand. To integrate biodiversity and promote sustainability, organic agriculture takes a broader systems approach, aiming to integrate organic principles into farming. With the aim to increase biodiversity, enhance ecosystem services, rebuild soil organic matter, and improve water cycles is very well adapted regenerative agriculture. These approaches also often intersect with broader sustainability goals, such as carbon sequestration, the promotion of local food systems, and improving the economic resilience of smallholder farmers.

Sustainable Intensification

Agricultural intensification refers to the increase in agricultural production per unit of input or maintaining production with fewer inputs (Struik & Kuyper 2017; Pellegrini & Fernández 2018). Sustainable intensification, on the other hand, is a process or system that aims to boost agricultural production and productivity without harming the environment or converting additional non-agricultural land (Pretty *et al*. 2011; Cassman & Grassini 2020). Building sustainable agricultural intensification and protecting both, the integrity of the land and the people involved in this are necessary to ensure the future quality and supply of agricultural products. Soil quality and natural biodiversity can be improved by optimizing agricultural methods such as tillage, crop rotation (Rasmussen *et al.* 2018), fertilisation, and the use of different agricultural chemicals (Fernández-Ugalde *et al*. 2009; Gómez *et al*. 2011; Lu *et al*. 2022; Iheshiulo *et al*. 2024). More efficient land use (e.g., zero tillage) can also help to reduce agricultural greenhouse gas emissions and future loss of natural habitats and contribute to soil carbon sequestration (Mondal *et al*. 2023). Agricultural intensification can have a positive impact on improving the economic and social conditions of farmers, resulting in increased food security and more job opportunities for current and future generations (Garibaldi *et al*. 2017; Meyfroidt 2018; Rasmussen *et al.* 2018; Cassman & Grassini 2020) (Figure 2).

Organic Agriculture

Organic agriculture takes a broader systems approach, aiming to integrate organic principles into farming to promote sustainability and biodiversity. This often involves reducing reliance on synthetic chemicals, focusing on soil health, and supporting wildlife habitats through diversified farming systems. Organic agriculture is an integrated farming system focused on environmental conservation, reducing dependence on chemical pesticides and fertilisers, and promoting agricultural sustainability. Key features of this approach include the avoidance of chemical pesticides, the widespread use of organic fertilisers, the preservation of biodiversity, crop rotation, and the incorporation of fallow periods (Ma & Zhuge 2024). According to the definition of the Association of Organic Agriculture of the Slovak Republic, the term organic agriculture refers to a system favourable to the environment, the goal of which is a sustainable agroecosystem, that primarily uses local and renewable resources and organically friendly technologies and at the same time its procedures minimal environmental damage. Organic agriculture increases the ability to face the adverse effects of climate change by reducing greenhouse gas emissions (Yue *et al*. 2023). It creates efficient and environmentally friendly agricultural systems resistant to climate change such as temperature fluctuations and drought, and that prevent soil erosion (Yu & Wang 2024). This approach to land and food production provides solutions to most of the problems agriculture is facing currently (Yue *et al*. 2023; Dhakal *et al*. 2024).

More than 100 countries around the world are currently publicly supporting organic farming standards (Seufert *et al*. 2017), which are based on standards developed by the International Federation of Organic Agriculture Movements (IFOAM). Organic standards cover various fields such as crop cultivation, animal husbandry (Yu & Wang 2024), beekeeping, and aquaculture. They include activities that are prohibited or restricted as well as activities that are required or recommended. An organic agri-

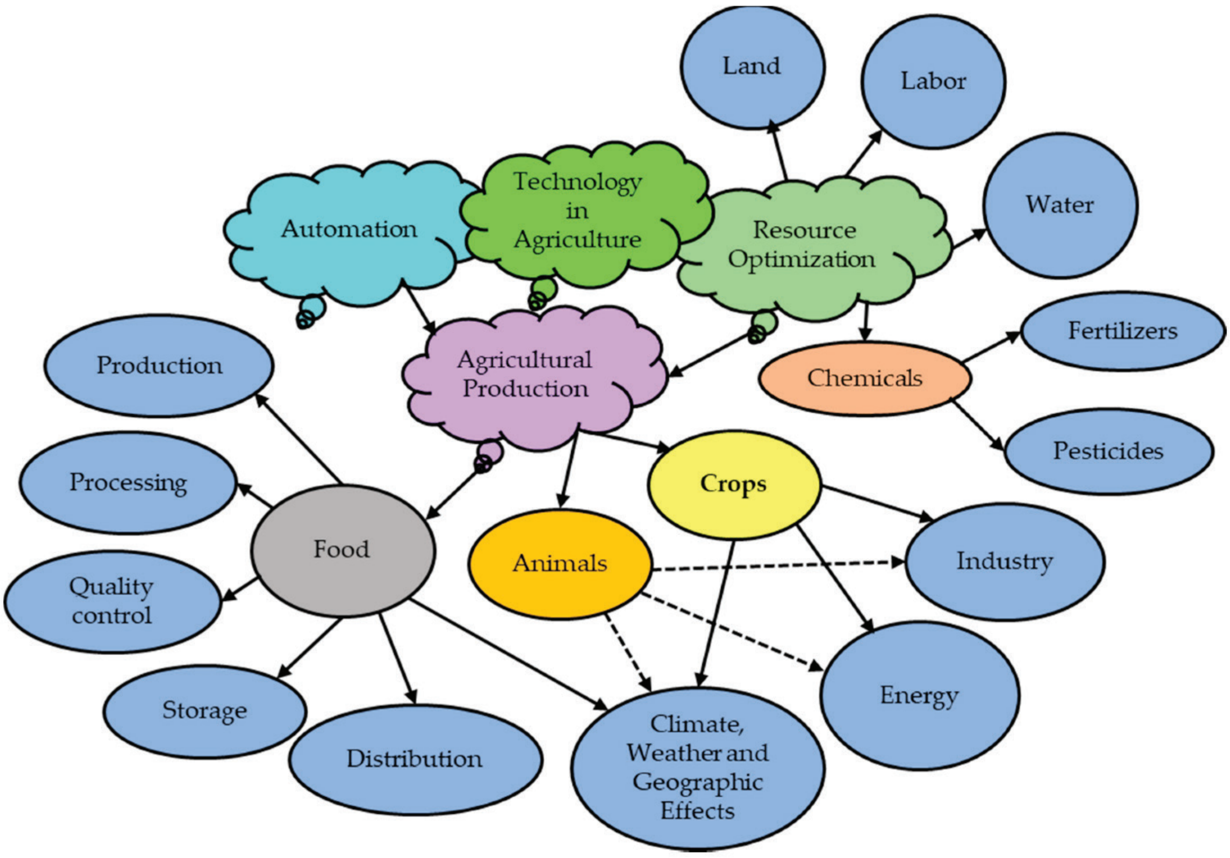

Figure 1. Key driving factors related to technology in advanced agriculture.
This list highlights the primary activities and factors within agriculture that necessitate advanced technology. It is not intended to be exhaustive, as there are numerous other driving factors and activities that also require advanced technological solutions (adapted from Khan *et al.* 2021).

culture system can be defined by the following five basic features: (1) respect for the environment and animals, (2) promotion of sustainable crop production methods, (3) use of non-chemical fertilisers and agents on pest, diseases and weed control, (4) production of high-quality food, and (5) prohibition of the use of genetically modified (GM) crops (Lairon 2010; EU Regulation 2018/848). Compliance with organic standards is verified annually through inspections carried out by accredited representatives (Seufert *et al*. 2017). For this reason, it is essential to keep records of all farming activities.

The Effect of Organic Agriculture on Crop Production Quality

Discussions are still ongoing about the nutritional composition of conventionally and organically grown crops. In general, it is proved that crops grown organically contain higher concentrations of key nutrients (Ma & Zhuge 2024) and lower levels of nitrates. They also contain higher concentrations of phytochemicals, flavonoids, antioxidants, phenolic compounds (Ren *et al*. 2017), and vitamin C (Hallmann & Rembiallkowska 2006; Golubkina *et al*. 2018). On the other hand, the concentration of proteins is lower compared to conventional agriculture (Krejčířová *et al*. 2006; Bilsborrow *et al*. 2013) and nitrate levels (Herencia *et al*. 2011). In some studies, no significant differences between conventional and organic production systems have been observed in terms of nutritional composition in the crops, especially regarding the concentration of proteins, minerals, and trace elements (Mäder *et al*. 2007) or phenolic compounds (Mazzoncini *et al*. 2015).

In the work of Giusti *et al*. (2018), differences

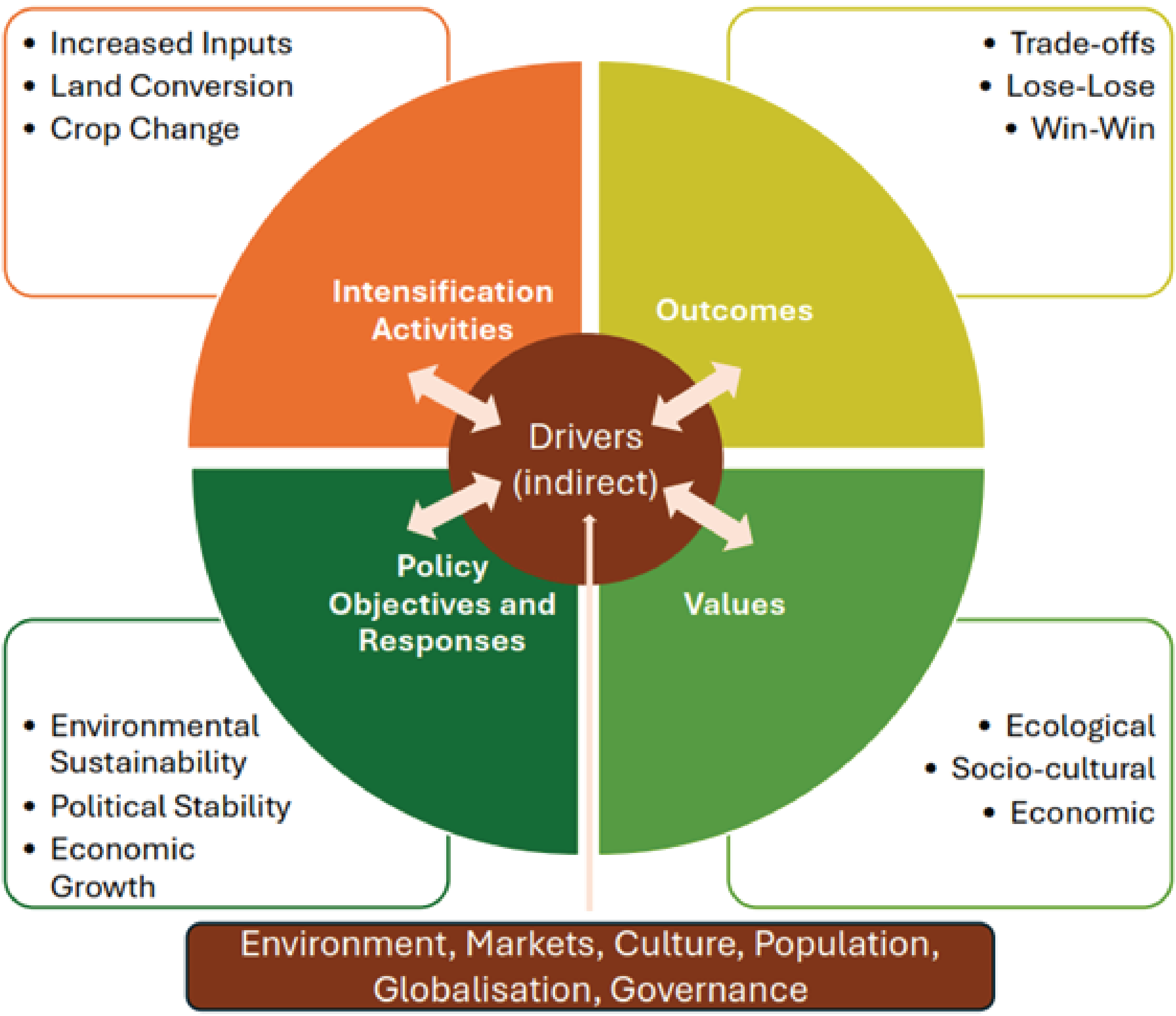

Figure 2. The agricultural intensification process and its possible outcomes (adapted from Rasmussen *et al.* 2018).

in the nutritional composition of conventionally and organically grown legumes were analysed in terms of the content of phenols, anthocyanins, flavonoids, and their antioxidant capacity. Results show that organically grown crops have higher concentrations of phenolic acids, especially gallic, caffeic, syringic, and ferulic acids. They also show higher antioxidant capacity compared to conventional approaches. The total protein content was determined in various samples of legumes, such as pea (*Pisum sativum* L.) and bean (*Vicia faba* L.) varieties grown on a conventional and organic production systems. The results show that the protein content was significantly higher in crops grown under organic farming conditions (Walter *et al*. 2022). However, in older literature, it is more often stated that the protein content is higher in conventionally grown crops (Krejčířová *et al*. 2006; Bilsborrow *et al*. 2013). In the work of Latvian scientists, it was found that the protein content in peas, beans, and soybeans (*Glycine max* L.) does not statistically significantly differ according to the cultivation system (Sterna *et al*. 2020). Based on these results, it can be assumed that the content of proteins and other nutrients is influenced by both, the agricultural approach and other factors, such as genotype and external environment like climatic conditions, soil quality, precipitation, and fertilisation. However, a fundamental improvement in the nutritional composition of cereals in terms of protein content was found in a study of 22 varieties of spring barley grown organically and conventionally for two consecutive years. It has been proven that the effect of the organic cultivation system increased the average content of the lunasin peptide from 47 to 92% (Legzdina *et al*. 2014). Lunasin is a peptide that has potential in the prevention and treatment of cancer in humans (Wan *et al*. 2017).

Menkovska *et al*. (2017) enzymatically determined the content of β-D-glucan, as the basic component of soluble dietary fiber in selected cereals, in samples of oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), rye (*Secale cereale* L.), and wheat (*Triticum aestivum* L.). Even though the values of β-D-glucan content were not significantly different between crop samples of conventional and organic cultivation, they conclude that organic agriculture is very promising in producing cereals with positive health benefits in terms of dietary fiber content.

Available evidence from most scientific studies indicates that the occurrence and concentrations of mycotoxins produced by the pathogenic species of the fungus *Fusarium* ssp. are lower in organic compared to conventional approaches. Most studies also indicate that crop rotation, high organic matter content, and high biological activity of microorganisms in the soil, as well as the minimization of the use of mineral nitrogen fertilisers, some fungicides, and herbicides are associated with a lower risk of contamination of cereals by *Fusarium* mycotoxins (Bernhoft *et al*. 2022).

Organic Agriculture in the Slovak Republic

Since 1990, Slovak agriculture has undergone numerous reforms. The entry of the Slovak Republic into the European Union meant the acceptance of obligations in agricultural and environmental legislation. Organic and environmental limits were applied, which meant the usage of chemicals and agricultural machinery to a much lesser extent. The result was a lower burden on individual components of the country. With a decrease in intensification, or with a sustainable approach to the agricultural soil, there was a significant decrease in the application of industrial fertilisers in agriculture. Currently, more attention is paid to greening measures and to the support of organic agriculture, which is much more sensitive to nature and its protection, the protection of natural resources, and the environment (Izakovičová *et al*. 2022).

The topic of organic agricultural production in the Slovak Republic is dealt with by the Department of Organic Agricultural Production (OEPV), a part of the Central Control and Testing Institute in Agriculture located in Bratislava (ÚKSÚP). The professional duties and responsibilities are stated in the EU legislation, namely 58 THE LAW of February 2, 2023, which amends Act no. 282/2020 Coll. on organic agricultural production as amended by Act no. 350/2020 Coll. (Slov-Lex 2023).

In the long-term horizon from 1993 to 2020, a positive trend in the introduction of organic agriculture was recorded with an increase of 11.45% (Izakovičová *et al*. 2022). Increasing the areas of organic agriculture to at least 13.5% by 2030 is one of the main goals of the SR 2030 Environmental Strategy in sustainable land management (MŽP SR

2019). As of October 31, 2023, the total area of agricultural land cultivated organically is 228,323.76 ha, and 1,311 operators are registered in the system of organic agricultural production (ÚKSÚP 2023), and with an increasing trend (Table 1).

The objectives of the European Commission presented in the Farm to Fork strategy have the task of moving the EU food system to a healthier and more sustainable level, and the area used for organic agriculture should increase within European countries to 25% of the total agricultural land by 2030 (European Commission 2020b).

Despite the increased interest in organic agriculture in the Slovak Republic, many shortcomings are still observed, such as the poorly developed distribution of organic products and their low sales on the domestic market. The availability of organic products is relatively limited, and the lack of strong competition fails to create the pressure needed to lower the high prices of organically produced goods, making them less accessible to final consumers (Némethová *et al*. 2017).

Climate-Smart Agriculture

Climate-Smart Agriculture involves practices that support both agricultural productivity and climate adaptation. It includes things like improving water use efficiency, diversifying crops, using drought-resistant varieties, and integrating systems that sequester carbon. It's essentially about increasing the resilience of farming systems to climate-related risks while reducing agriculture's contribution to greenhouse gas emissions. Climate change represents a significant and growing threat to global food and nutrition security.

Climate-smart agriculture is an approach that aims to make agriculture more sustainable in the era of climate change (Zhao *et al*. 2023; Vishnoi & Goel 2024). It is a strategy of introducing new agricultural technologies and practices to support production to adapt to and mitigate climate change (Kaczan *et al*. 2013; Lipper *et al*. 2017; Zhao *et al*. 2023). It aims to provide internationally applicable agricultural management concepts for food security in a changing climate (Zhao *et al*. 2023; Vishnoi & Goel 2024) that could serve as a basis for policy support and proposals from multilateral groupings of states such as the Food and Agriculture Organization (FAO) of the United Nations (UN). Climate-smart agriculture refers to agricultural methods that can increase production, increase plant resistance to pathogens and diseases, and reduce greenhouse gas emissions while helping to achieve initiatives in food security and development (FAO 2013; Zhao *et al*. 2023; Vishnoi & Goel 2024).

The adoption of Climate-Smart Agriculture (CSA) varies across the continents (Figure 3). According to Li *et al*. (2024), scholars from Asian and African countries have contributed a significant portion of the literature in this field. In contrast, the literature from Europe, Oceania, and the Americas is generally limited and shows a declining trend. This uneven geographic distribution of CSA adoption literature can be attributed to the differing pressures on food supply across continents. Africa and Asia face greater challenges in producing enough food to feed their populations compared to Europe, Oceania, and the Americas (Do & Ho 2022; FAO 2023).

T a b l e 1

The total area of agricultural land registered in organic agriculture production in the Slovak Republic as of 30/11/2024 (in ha). As of 30/11/2024, there are 1,335 operators registered in the organic production system in Slovakia (of which there are 967 with land) (ÚKSÚP 2024).

Land status	Agricultural land	Arable land	Permanent grasslands	Orchards	Vineyards
Organic	233036.77	76683.11	154354.83	1577.72	421.11
III. year of conversion	127.11	0	0	58.09	69.02
II. year of conversion	22546.49	7179.72	15113.89	192.26	60.62
I. year of conversion	13320.52	5115.19	8128.37	24.20	52.76
Total	269030.89	88978.02	177597.09	1852.27	603.51

As a result, researchers have focused more on CSA adoption in these regions (Li *et al*. 2024).

Climate-smart agriculture seeks to minimize or eliminate greenhouse gas emissions associated with the production of food, fibre and fuel. It approaches soil and crops to enable them to act as carbon reservoirs and absorb carbon dioxide (CO_2) from the atmosphere. CO_2 subsequently reaches the soil through the plant and its root system, where it forms an important part of soil organic matter called humus. Better carbon sequestration can be achieved through many sustainable agriculture practices, such as no-tillage, leaving crop residues, crop rotation, or intercropping (Chen *et al*. 2009; Clark *et al*. 2017). Hazra *et al*. (2019) proved that the rotation of fields with maize (*Zea mays* L.) and wheat improves soil aggregation and carbon sequestration in the long term. One of the ways to increase the content of organic carbon in the soil is to alternate cereals with legumes. The results of this experiment indicate that the inclusion of legumes could increase soil organic carbon retention by up to 10%, while also increasing the total yields of rotated crops (van der Pol *et al*. 2022). It has also been found that even no-till can increase soil organic carbon while reducing greenhouse gas emissions (Curtin *et al*. 2000). The use of integrated nutrient management also has a positive effect on crop yield, soil carbon content, and nutrient availability for crops (Choudhury *et al*. 2018). Leaving crop residues in the field after harvest improves soil health, carbon storage, and soil moisture (Turmel *et al*. 2015).

Climate-smart agriculture also aims to improve agricultural techniques and approaches to increase crop productivity and income while minimizing environmental impact. It also contributes to improving food and nutritional security (Teklu *et al*. 2023). In general, climate-smart agriculture can provide an efficient way of global agriculture and rural development sustainably in the presence of changing weather patterns (Campbell *et al*. 2014; Zhao *et al*. 2023). Smart water practices present opportunities for farmers to mitigate water stress caused by climate change. Innovative water conservation technologies such as rainwater harvesting, mulching, or terracing can save costs and provide high-quality water throughout the year while increasing farmers' yields and incomes (Karpouzoglou & Barron 2014; Botha *et al*. 2015). At the same time, these systems create water efficiency and allow access to water during pe-

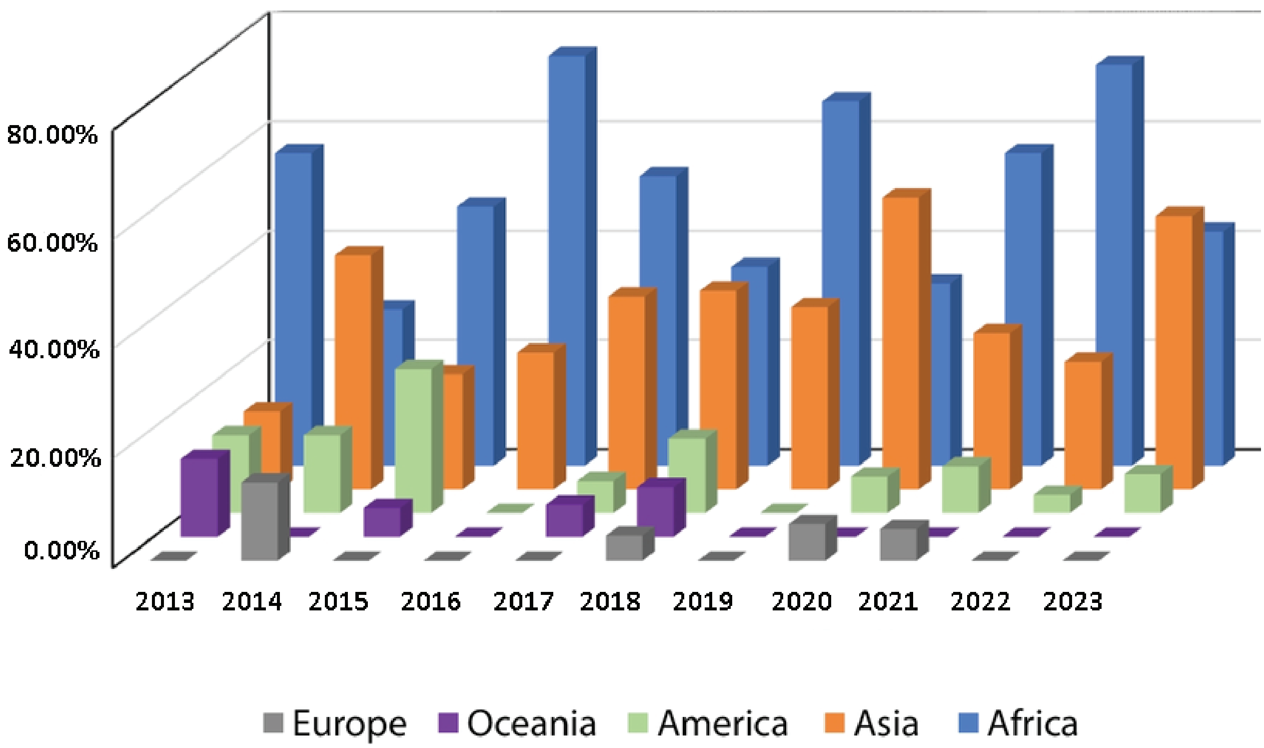

Figure 3. Distributions of the scientific studies dealing with Climate-smart agriculture by continent in the years period 2013 – 2023 (adapted from Li *et al.* 2024).

riods of water deficiency (Patle *et al*. 2020). Despite many positives, the concept of climate-smart agriculture is still evolving and there is limited research on the relationship between climate-smart agriculture and sustainable agriculture, as well as how climate-smart agriculture practices can be implemented to ensure long-term food and nutrition security (Sarker *et al*. 2019). Challenges in climate-smart agriculture persist, including issues related to limited agricultural water resources, climate variability and change, agricultural greenhouse gas emissions, and the integration of information resources (Zhao *et al*. 2023).

The Effect of Climate-Smart Agriculture on Crop Production Quality

C-smart agriculture is an effective approach to improve soil water retention (12%) and increase grain yield (66%) of maize (Zizinga *et al*. 2022). Research conducted in southern Ethiopia found that soils that were managed under CSA practices had nearly twice as much total plant-available nitrogen and phosphorus as conventional practices. At the same time, the carbon reserves in the soil managed by CSA practices were increased three to seven times, and the wheat yield was higher by 30−45% compared to conventional agriculture (Tadesse *et al*. 2021). CSA is also recognized as an essential pathway to food security and rural poverty reduction in a changing climate and poverty-stricken, flood-prone, and soil-salinized areas such as Bangladesh (Akter *et al*. 2022). The positive impact of CSA on agricultural production has also been noted in the Maharashtra region of India, which suffers from severe water shortages during the dry season. Drought can be solved using the practices of this agricultural system with various irrigation water technologies, such as digging wells, rainwater harvesting, or other methods of groundwater extraction. Combined with integrated nutrient management methods, such as the use of animal manure, vermicomposting, or incorporating straw residues into the soil, it can improve the efficiency of water and fertiliser uses. At the same time, it can increase agricultural productivity and reduce the amount of agricultural water, fertilisers, and greenhouse gas emissions (Khatri-Chhetri *et al*. 2019).

Optimizing sowing and harvesting dates, reducing the number of chemical fertilisers, and adjusting irrigation schedules had a very positive impact on total crop yields in rice (*Oryza sativa* L.) cultivation in the delta of Mekong River in Vietnam (Ho & Shimada 2019). In Zambia, central Africa, conservation agricultural measures such as spreading post-harvest crop residues on farmland or alternating between legumes and cereals are used. These measures in Zambia have the potential to increase soil fertility and carbon sequestration capacity, thereby significantly increasing average grain yields and effectively ensuring local food security (Kaczan *et al*. 2013). Farmers in Namibia have increased crop yields by applying nutrient-rich earthworm compost leachates, practicing hydroponic cultivation, and planting mushrooms along the coast of the Namib Desert, while also collecting mist water to conserve irrigation water, or mixing it with seawater and using it for irrigation directly to the roots of crops. Through these measures, Namibia has mitigated the food insecurity crisis and increased its agricultural land adaptability to climate change (Mupamwa *et al*. 2019).

The system of climate-smart agriculture is mainly aimed at developing countries more threatened by the impact of climate change, such as the countries of sub-Saharan Africa or South Asia, as can also be seen from the research above. For countries with developed agriculture, high economic efficiency, and higher land areas per capita, these practices focus primarily on reducing greenhouse gas emissions while improving production efficiency (Kaczan *et al*. 2013; Long *et al*. 2016).

Regenerative Agriculture

Regenerative Agriculture focuses on rebuilding soil organic matter, improving water cycles, increasing biodiversity, and enhancing ecosystem services. It includes practices like cover cropping, agroforestry, rotational grazing, and reducing tillage. The goal is to make the land more resilient to climate change and improve soil health. Regenerative agriculture is a holistic approach to agriculture based on six principles of agroecosystem restoration: (1) understanding that each soil and soil microbiome has its environmental specificities, (2) minimizing external interventions into the soil (e.g. tillage, or the use of synthetic fertilisers and pesticides), (3) maintaining soil cover throughout the year, (4) maintaining living plant root systems in the soil for as long as possible, (5) increasing biodiversity, and (6) integrating farm animals (Eckbert & Rosenzweig 2020) (Figure 4). This agricultural method seeks to implement the above principles to restore healthy agricultural ecosystems and eliminate soil degradation, loss of biodiversity, and even a decrease in economic profitability. There are many different definitions and approaches to regenerative agriculture. Instead of a universal approach, it is necessary to adapt all the mentioned methods to the specific agricultural and climatic environment in which they are used. Some regenerative agriculture practices overlap with other forms of sustainable agricultural practices, such as organic or CSA (Khangura *et al*. 2023).

The Effect of Regenerative Agriculture on Crop and Soil Quality

LaCanne and Lundgren (2018) assessed the effects of regenerative and conventional approaches of maize production systems on ecosystem services, profitability, and productivity. It was found that pests were 10 times more common in fields treated with insecticides than in fields with a regenerative system. Regeneratively managed fields showed 29% lower maize production, but 78% higher profits compared to traditional agriculture. The gain was mainly related to the effect of the agricultural approach on soil organic matter, not crop yield.

One of the mechanisms used in regenerative agriculture is the integration of earthworms into the soil. Hodson *et al*. (2023) conducted an experiment in which 5 varieties of spring wheat were grown in the presence and absence of earthworms under regular irrigation and drought conditions. The results show that the amount of plant biomass was greater in samples grown in the presence of earthworms in the soil. The presence of earthworms reduced the effect of drought on plant biomass and slowed the rate of soil drying. The presence of earthworms also has a positive effect on the soil microbiome in terms of suppressing plant pathogens and promoting plant growth.

The research in regenerative agriculture has also shown that tillage can disrupt and reduce populations of saprophytic and mycorrhizal fungi, thereby compromising soil health (Frey *et al*. 1999; Kabir *et al*. 2005; Brito *et al*. 2012; Dai *et al*. 2015) and on the other hand, studies indicate that regenerative agriculture enhances soil health by increasing microbial diversity and richness (Mącik *et al*. 2023; Singh *et al*. 2023; Khangura *et al*. 2023). One example of how the increased biodiversity of the soil microbiome affects positively the quality and added value of crop production is the amino acid ergothioneine. Ergothioneine is an amino acid with strong antioxidant and anti-inflammatory properties that is produced by a variety of soil fungi and mycobacteria. Crops such as maize, soybeans, and oats cultivated conventionally were found to contain 30% less ergothioneine compared to regeneratively grown crops (Beelman *et al*. 2021).

Agriculture and Biodiversity

Biological diversity is a phenomenon representing the diversity of all living organisms on the Earth, such as millions of species of plants, animals, and microorganisms. Many of the ecosystem functions provided by biodiversity, such as pollination of flowers, retention of nutrients in the soil, resistance to weeds or suppression of pathogens are important to produce crops and therefore can also be classified as ecosystem services (Duru *et al*. 2015; Manning *et al*. 2019). In addition to the mentioned functions, biodiversity also supports and stabilizes other ecosystem functions, such as biomass production or carbon storage in the soil (Balvanera *et al*. 2006; Cardinale *et al*. 2011; van der Plas 2019).

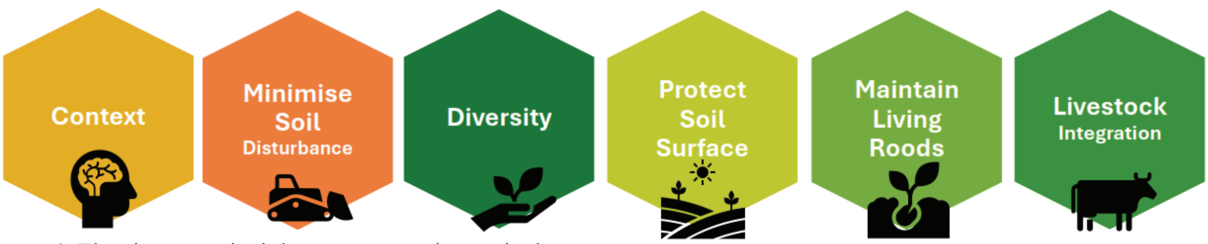

Figure 4. The six core principles to regenerative agriculture.

Endangerment of Biodiversity Due to Conventional Agriculture

The intensive use of conventional agricultural practices, such as the use of irrigation systems, tillage, ploughing with the use of heavy machinery, fertilisers, and pesticides, has led to one of the most fundamental environmental threats in the last fifty years − the loss of biodiversity (Barros-Rodríguez *et al*. 2021; Cozim-Melges *et al*. 2024). In addition to the global loss of biodiversity, one of the main current problems is the increasingly large-scale extinction and fragmentation of natural ecosystems (Wolff *et al*. 2018). The consequences arising from these problems are not only related to genetic loss but also to ecosystem services that, in addition to well-being, guarantee the preservation of human life (Jennings *et al*. 2016; Aerts *et al*. 2018). Agricultural systems often suffer from reduced biodiversity, making them more susceptible to pathogens, pests, and abiotic stresses such as drought. The reliance on synthetic fertilisers and pesticides not only harms the environment but also negatively impacts plant production (Cozim-Melges *et al*. 2024). As a result of the addition of nitrogen to the soil, a reduction in biodiversity is observed, while its reduction is more significant when using fertilisers containing NH^{4+} ions and those containing NO^{3-}. This loss of species diversity due to nitrogen application is more pronounced in warmer regions, leading to lower yields of nitrogen-sensitive crop species such as legumes or non-vascular plants (Fay *et al*. 2015). A reduction in microbial biodiversity was also found to occur after phosphorus addition to soil (Fay *et al*. 2015), however fertiliser regime, followed by soil properties, and available P are the main factors impacting the soil microbiome (Wang *et al*. 2018). Nitrogen pollution of terrestrial ecosystems also causes species loss through processes of eutrophication and acidification with serious consequences for community composition throughout the food chain (Bobbink *et al*. 2010).

Biodiversity is also negatively affected by using herbicides, which, in addition to their primary goals such as the elimination of weeds, also affect non-target organisms, mainly related to the soil microbiome (García-Delgado *et al*. 2018). Other chemical preparations are also used in agriculture to kill fungi, nematodes, insects, and rodents, which also affect the biodiversity of the area in which they are used and have a particularly strong and negative effect on soil microorganisms (Mulla *et al*. 2020).

Losses and fragmentation of suitable habitats due to the intensification of agriculture also partially result in the decline of populations of native species within agroecosystems (Winfree *et al*. 2009), concerning mainly pollinators such as the bumblebee (Carvell *et al*. 2015). As a result of agriculture, which is a key activity for the development of society and the maintenance of human life, a huge number of natural ecosystems are converted into monocultures, which fundamentally contribute to greenhouse gas emissions (Bogužas *et al.* 2022; Zugasti-López *et al.* 2024) and loss of biodiversity (Cozim-Melges *et al*. 2024; Martinez *et al*. 2024).

Cultivating the soil with agricultural heavy machinery may contribute to aerating the soil and mixing it with supplied fertilisers, however, these processes also have their negatives (Derpsch *et al.* 2024). During tillage, there are significant changes in the biological and chemical properties of the soil and a greater possibility of erosion due to a decrease in soil moisture and organic matter content (Lal *et al*. 2013; Groenigen *et al*. 2016; Derpsch *et al*. 2024). These changes harm the populations of earthworms (*Lumbricidae*) and soil microorganisms, which significantly contribute to greater soil quality by improving its structure and increasing nutrient availability (Blouin *et al*. 2013). Conventional tillage techniques have been found to significantly reduce the population of earthworms, with immature individuals being particularly affected, which make up 76−90% of the total population (Domínguez *et al*. 2016). Navarro-Noya *et al*. (2013) proved negative changes in soil microbiome communities due to tillage, especially in genera of soil microorganisms such as *Actinobacteria*, *Betaproteobacteria* and *Gammaproteobacteria*.

Biodiversity Protection by Using Sustainable Agricultural Methods

To mitigate the decline of native species such as pollinators, agro-environmental schemes funded by the EU have been introduced within agro-ecosystems (Council Regulation (EEC) No. 2078/92). Based on these regulations, financial compensations are provided to farmers for carrying out agricultural practices that have a beneficial effect on biodiversity, such as less intensive cultivation of cultivated land or the creation of new habitats on uncultivated land. Agro-environmental schemes have been shown to benefit natural populations of birds, bees, butterflies, and plants, leading to increased species biodiversity and abundance in specific habitats (Carvell *et al*. 2007; Pywell *et al*. 2011; Pywell *et al*. 2012). In a study by Carvell *et al*. (2015), the impact of agro-environmental schemes on the population of natural pollinators, such as the bumblebee was investigated. Planting flower beds in areas with a high proportion of arable land has been noted to have a positive effect on pollinating insect populations.

The importance of plant-soil feedback through soil microbial communities in the relationship between biodiversity and ecosystem functioning is increasingly being advocated for agricultural practices today concerning monoculture crops. The mechanisms underlying biodiversity and ecosystem functioning relations are still actively debated. More and more results indicate that plant biodiversity affects underground microbial communities, which oppositely support the functionality of ecosystems below and above ground (Wagg *et al*. 2014; Prommer *et al*. 2020).

Modern agriculture maximizes yields in the short term and modern crops produce high yields in monocultures where they are supplemented with nutrients and pesticides. In such a case, increasing biodiversity in the form of diversification, i.e. adding other types of crops, is unlikely to increase the productivity of the main crop (Tamburini *et al*. 2020). However, increasing diversity can enhance other ecosystem functions and potentially reduce the reliance on pesticides, irrigation, and fertilisation (Manning *et al*. 2019; Cozim-Melges *et al*. 2024; Martinez *et al*. 2024). Diversification of crops also from monoculture to two-cultivar mixtures reduces the incidence of diseases (Zhu *et al*. 2000; Martinez *et al*. 2024; Altieri *et al*. 2024). Functional diversity is also a strong indicator of the multifunctionality of the agricultural ecosystem, in which weed growth is suppressed, nitrogen is better retained in the soil, plants are better supplied with inorganic nitrogen, and finally, there is also greater biomass production by plants and an increase in yields (Finney & Kaye 2017; Mahaut *et al*. 2019).

The Relationship Between Plant and Microbial Biodiversity

While many processes affecting the positive relationships between biodiversity and ecosystem functions are located above ground, a significant part of these mechanisms can also occur below the Earth's surface in the soil (Kaisermann *et al*. 2017; Mariotte *et al*. 2018). Organisms of the soil microbiome are responsible for these processes. Plant roots support the growth and activity of various microorganisms, including plant growth-promoting rhizobacteria, mycorrhizal fungi, endophytic bacteria, actinomycetes, nematodes, and protozoa, all of which can significantly influence plant health and growth (Figure 5). The interaction between plants and soil microbes is a complex, continuous, and dynamic process that takes place in the rhizosphere, a specialized zone around the roots. Plants engage with these microbes through various types of relationships, such as competitive, exploitative, neutral, commensal, and symbiotic (Chauhan *et al*. 2023).

For sustainable agricultural practices, a better understanding of these mechanisms is crucial (Mariotte *et al*. 2018). Beneficial soil microorganisms can positively influence plant nutrient acquisition from the soil, pathogen defence, stress tolerance, and overall productivity (Philippot *et al*. 2013; Finkel *et al*. 2017; Chauhan *et al.* 2023). Numerous studies have demonstrated that plant species vary in their impact on soil microbiomes (Bezemer *et al*. 2006; Yeoh *et al*. 2017; Fitzpatrick *et al*. 2018; Chauhan *et al*. 2023). Various plant traits are linked to root microbial diversity, and species-specific root exudates can influence the rhizosphere and soil microbiome (Hu *et al*. 2018). Physiology and root architecture of plants are also associated with the diversity of root microbial communities. Growing different plant species in the same soil can lead to an increase in the diversity of the soil microbiome (Philippot *et al*. 2013; Chauhan *et al.* 2023; Cozim-Melges *et al.* 2024; Martinez *et al*. 2024). In the study of Ke *et al.* (2021), it has been shown that the strength of interactions between plant and soil microbial communities can vary depending on how long the previous plant species has been grown in the same soil.

The diversity of plant species also affects the composition of the arbuscular mycorrhizal community (Šmilauer *et al*. 2020). Plants grown in previous

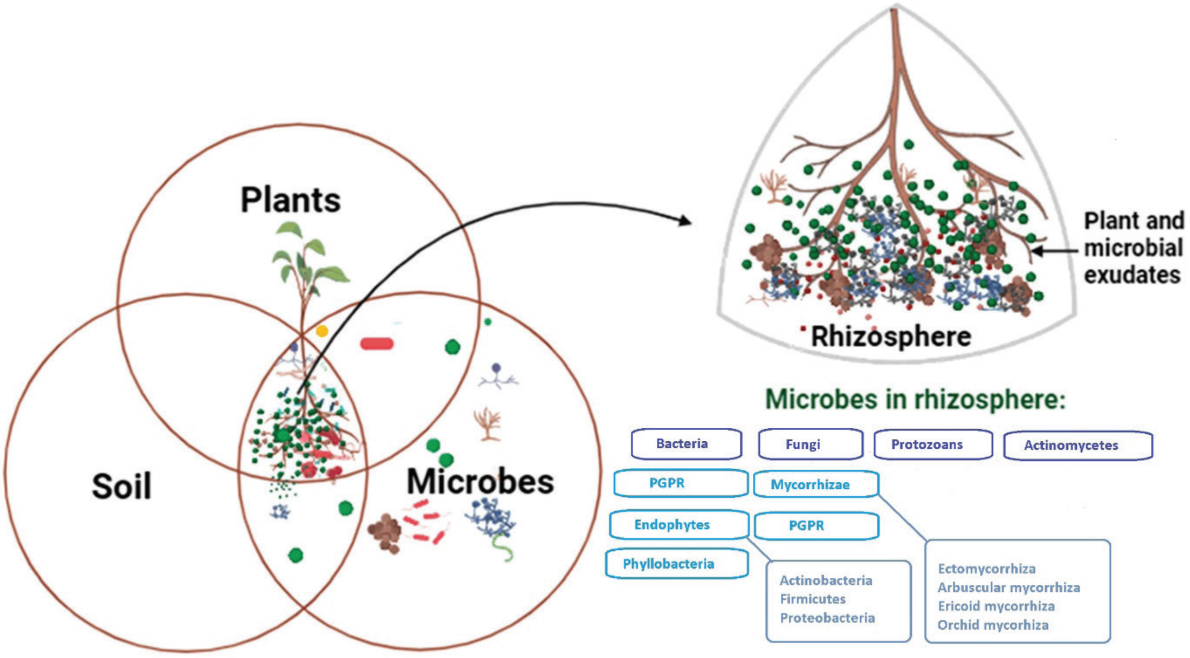

Figure 5. Various types of plant-microbe interactions in the rhizosphere, PGPR = Plant Growth-Promoting (Rhizo)Bacteria/Fungi (adapted from Chauhan *et al.* 2023).

growing seasons can influence the arbuscular mycorrhizal community composition of the currently grown plant through heritable factors (Bittebiere *et al*. 2020). In addition, abiotic factors also affect interactions between plants and microbes in the soil. Kaisermann *et al*. (2017) tested the hypothesis that drought influences plant-soil feedback, with subsequent effects on plant competition, by growing two grassland plant species in monoculture and in competition in soils that had either been exposed to a prior drought or not. The previous drought created a legacy effect on bacterial and fungal community composition, which reduced plant growth in soils with conspecifics and affected plant competitive interactions. Furthermore, both plant and microbial responses to a subsequent drought were influenced by the legacy of the prior drought on plant-soil interactions, with lasting effects on belowground communities that impacted plant-soil feedback and plant-plant interactions.

The effects of plants on the composition of the soil microbiome are particularly visible in the rhizosphere. Various substances are secreted into the soil by the rhizosphere, such as sugars, amino acids, organic acids, or dead root cells, which affect the activity and composition of the rhizosphere microbial community (Philippot *et al*. 2013). For the proper development of sustainable agriculture, it is essential to pay attention to these rhizosphere-mediated multitrophic interactions, which are weakened by breeding (Porter & Sachs 2020) or intensive conventional agricultural practices (Banerjee *et al*. 2019).

The diversity of soil microorganisms impacts the cycle of nutrients crucial for plants and the physical structure of the soil, or its aggregation capacity, which is an important ability to reduce erosion and hold water properly in soil. A growing body of evidence indicates that soil microbial diversity is closely associated with key functional aspects of soil that are essential for sustainable agriculture, such as the suppression of pathogenic microbes, plant matter decomposition, nutrient cycling, and the reduction of greenhouse gas emissions (Domeignoz-Horta *et al*. 2015; 2018; Glassman *et al*. 2018; Ou *et al*. 2019; Zugasti-López *et al*. 2024).

CONCLUSIONS

In conclusion, alternative agricultural practices such as regenerative, organic, climate-smart, and preservative methods offer promising solutions for addressing some of the most pressing environmental challenges of our time. Through the restoration and enhancement of soil health, these approaches not only increase soil organic carbon but also contribute to mitigating the impacts of climate change. Practices like minimization, mulch-till, and no-till agriculture have demonstrated tangible benefits in improving soil structure, enhancing water retention, and reducing soil erosion, all while maintaining or even increasing agricultural productivity.

However, the widespread adoption of these practices faces several challenges, including the need for farmer education, adjustments in management practices, and initial economic investments. While these techniques hold great potential, careful consideration of local environmental conditions, crop types, and long-term sustainability is essential for their successful implementation.

Ultimately, a holistic and integrated approach to agricultural systems − one that balances productivity with ecological health − will be key in building resilient agricultural landscapes that can support both global food security and environmental sustainability. Further research and policy support will be crucial in scaling these practices and ensuring their broader adoption across diverse agricultural systems.

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