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**CIRCULAR ECONOMY AND SUSTAINABLE  
PRACTICES IN REGENERATIVE AGRICULTURAL  
PRODUCTIVITY**

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**Introduction.** The industrial model of agricultural intensification, focused on the intensive use of non-renewable energy sources and their derivatives (such as mineral fertilisers and pesticides), has not generated sustainable development from an economic, ecological, and social point of view. The apparent success of this model has been built on the degradation of natural and social capital and on the transfer of ecological and health costs to society. The widening imbalance between ever-higher industrial input prices and stagnant agricultural production incomes has heightened farmers' economic vulnerability.

**Aim and tasks.** The study focuses on the circular economy and sustainable regenerative agricultural practices, while examining the limitations of a reductionist approach that focuses on short-term profit at the expense of economic, environmental, and social balance.

**Results.** Based on data obtained in long-term experiments carried out in the Republic of Moldova and Romania, the article supports the need for a transition to an alternative agricultural model, based on the use of local renewable energy sources, deep recycling in accordance with the circular economy, and the restoration of the function of the soil. Applying practices such as diversified crop rotation, including perennial legumes and composted organic matter, substantially reduces dependence on industrial input, increasing the resilience and competitiveness of agricultural systems. In rotations that included mixtures of alfalfa and perennial grasses, the application of compost led to an average increase in winter wheat production compared to unfertilised variants, and the supplementation with mineral fertilisers did not bring additional benefits and even caused decreases (0.10–0.16 t/ha) in yield.

**Conclusions.** The importance of this study lies in providing a conceptual framework for the reconfiguration paradigm of agricultural intensification. This study proposes practical and sustainable solutions adapted to the current conditions in Eastern Europe, with expansion potential for international application in the transition to agroecological systems aligned with the circular economy. Long-term experiments showed that in rotations that include perennial legumes and composted organic matter, the average yield of winter wheat increased by 0.52 t/ha compared to unfertilised variants. Simultaneously, additional fertilisation with mineral fertilisers did not result in additional gains and, in some cases, reduced yields, which underlines the efficiency of organic inputs in diversified rotations.

**Keywords:** Circular Economy, Crop Rotation, Renewable Resources, Soil Health, Sustainable Agriculture.

## **1. Introduction.**

The Green Revolution, an industrial intensification model, is deeply rooted in modern agriculture. The basic principle of this model is to promote the use of non-renewable energy resources, but also their derivatives, namely mineral fertilisers, pesticides to combat weeds, diseases, and pests, and the fuel necessary for intensive mechanisation (Hamdan et al., 2022; Pingali, 2023).

Although this model generated, on the surface, a substantial increase in agricultural production, it failed and could not ensure sustainable development from an economic, ecological and social point of view. The so-called success of industrialised agriculture was made possible by the progressive degradation of natural and social capital, along with the systematic externalisation of negative environmental and public health costs. This situation masks the structural inefficiencies of the system. As a result of not including the restoration of degraded ecosystems, agricultural prices do not faithfully reflect the real cost of production, primarily if they refer to the measures taken against climate change or the treatment of various diseases generated by the accumulation of toxic substances used in the agricultural process (Caglar & Askin, 2023; Hamdan et al., 2022; Pingali, 2023).

The reductionist nature is the essence of this model. Because it focuses on punctual interventions and the short-term maximisation of production, it leaves the real complexity of agro-ecosystems on the secondary level. The latter brings detrimental benchmarks for building sustainable agricultural systems and tilts the balance towards preventing degradation, unlike the reductionist model, which emphasises the temporary control of irregularities (Bressanelli et al., 2022; Stempfle et al., 2024; Xie et al., 2025).

In this context, adopting and implementing circular economy elements has emerged as a sustainable and innovative alternative to the linear and intensive agricultural model. The circular economy promotes reducing the use of non-renewable resources, valorising nutrient cycles through internal recycling, increasing biodiversity, and improving soil health and water quality.

Among the circular economy strategies in this direction are crop rotation, agroforestry, cover crops, and consolidation and collaboration between actors along the food chain. The circular economy proposes a profound transformation of the agricultural production paradigm. The transition to circular and regenerative agricultural systems is not only possible but also necessary in the current context of the climate crisis and pressure on natural resources (Batlles-de-laFuente et al., 2022; Feodorov et al., 2022; Lakatos et al., 2024; Pacurariu et al., 2021; Topa et al., 2025).

Long-term experiments in the Republic of Moldova and Romania, complemented by the growing experience of farmers applying agroecological principles that demonstrate the feasibility of these solutions. Practices such as diversified crop rotation, integration of perennial legumes, use of compost, and reduction in tillage intensity simultaneously restore soil fertility, reduce dependence on industrial inputs, and strengthen the resilience of agricultural systems to climate variability.

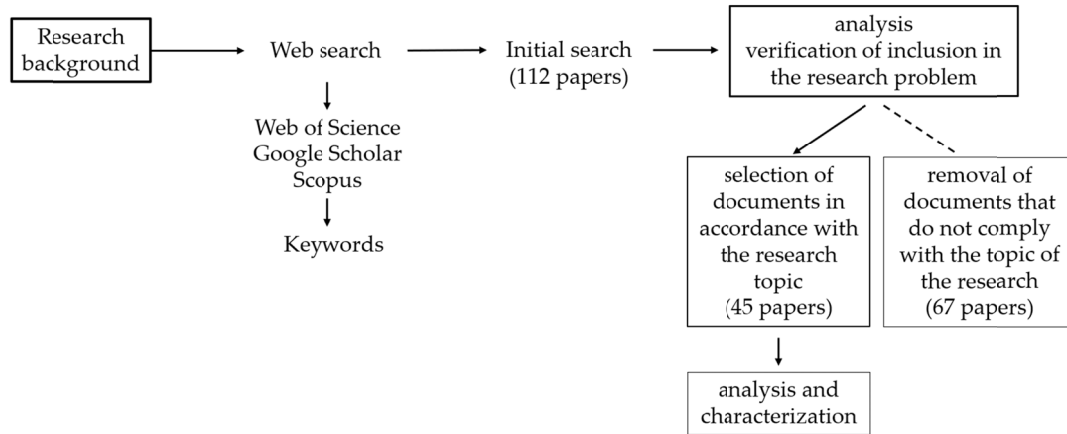
This study begins with a substantiated critique of the limits of the industrial agricultural model. It proposes an alternative vision, supported by empirical data, for the transition towards a sustainable agricultural system integrated into the circular economy. Its relevance for the scientific community lies in providing a conceptual and applicative framework that connects ecological principles with agricultural practices in a way adapted to the regional specificity of Eastern Europe, but with potential for global expansion. Thus, this study contributes by deepening the understanding of the mechanisms of agricultural transition and by identifying validated solutions oriented towards a sustainable and equitable agricultural future.

## **2. Methodology.**

This study conducted a review of the academic literature to obtain a comprehensive background on the stage of agriculture in the current economic context in the Republic of Moldova and Romania, the interplay between regenerative agriculture and the circular economy, and the evaluation of the importance of crop rotation in the circular economy.

In this regard, the database query was performed using a combination of keywords: “circular economy”, “crop rotation”, “renewable resources”, “soil health”, “sustainable agriculture”, “agriculture in food security”, “CE in agriculture”, “economic context of agriculture in Romania”, “economic context of agriculture in Republic of Moldova”. A total of 112 papers were initially

screened, and 45 papers were selected for final analysis, categorisation, and characterisation of the background in the economic context and the current state of agriculture. These documents served, on the one hand, to understand the current context of agriculture and, on the other hand, to analyse the interplay between regenerative agriculture and the circular economy (Figure 1).



**Fig. 1. Research Methodology for Background Context.**

The study is based on a series of experiments conducted by the Field Crops Research Institute Selecția in Bălți of the Republic of Moldova (2024), on chernozems typical of the steppe region of northern Moldova. Relevant data were collected under real farm conditions, both in the Republic of Moldova and Romania, to assess the applicability of these agroecological practices in commercial systems.

The main experiment on crop rotation was initiated in 1962, and in 1965, permanent monocultures were introduced, cultivated both with and without fertilisation, on the same soil types. The experimental scheme includes eight crop rotations in which the share of cover crops, such as sugar beet (10-30%), corn (20-40%), and sunflower (10-20%), varies between 40% and 70%. Winter wheat is present in a proportion of 30% in all rotations (Boincean & Dent, 2019a). However, it is preceded by different crops: early harvested crops and corn intended for silage or grain. Each experimental plot dedicated to the rotation had an area of 283 m<sup>2</sup> and was repeated thrice for statistical accuracy.

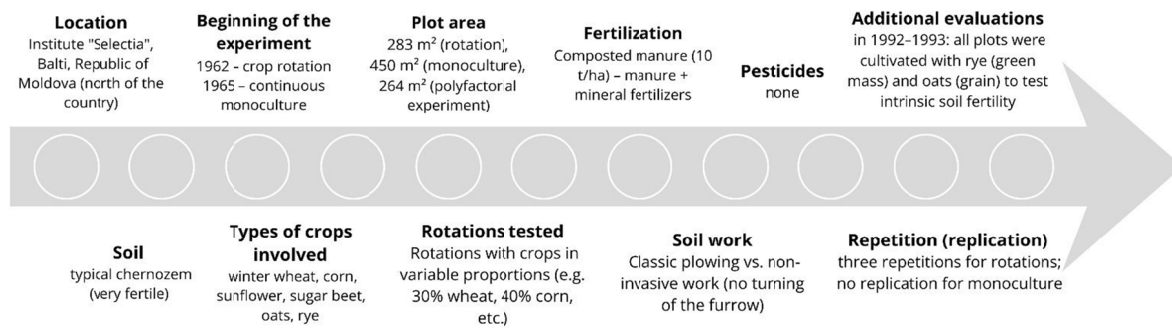
In comparison, the plots dedicated to monoculture are larger (450m<sup>2</sup>), but are not replicated. After completing three complete rotation cycles in 1992 and 1993, the rotations were temporarily suspended to evaluate intrinsic soil fertility. This evaluation was carried out by growing two test crops, rye for green mass and oats for grain, in all experimental plots.

The fourth rotation cycle began in 1994. However, to study in detail the effect of fertilisation in interaction with rotation, two distinct rotations were selected: Rotation 3, in which fertilisations were applied, and Rotation 7, in which no fertilisation was used. In addition to these experiments, a multifactorial experimental design was implemented that explores the interactions between the type of rotation (with or without perennials, e.g. lucerne), the soil tillage methods (ploughing versus non-invasive non-tillage methods), and the fertilisation regime.

In this case, three variants were analysed: an unfertilised control, fertilisation with composted manure, and combined fertilisation (manure and mineral fertilisers).

An average of 10 t/ha of manure was applied, combined with variable doses of mineral nutrients. In the first rotation (which included perennial grasses), 10 t/ha of manure supplemented with active substances (N12.8 P23.4 K24.2 kg)/ha was used. In the second rotation, the same amount of manure was supplemented with a higher dose of nitrogen (N38.6 P24.2 K24.2 kg/ha). The experiments were carried out without applying pesticides to simulate agroecological conditions and to test the capacity of agro-food systems to function without external chemical interventions.

Each experimental variant was replicated three times, and the area of a plot was 264m<sup>2</sup>. In parallel, continuous monoculture experiments with winter wheat, sugar beet, sunflower, and maize were carried out under the same conditions as in the multifactorial experiment, but without repetitions. This integrated approach allowed for the comprehensive assessment of the effects of crop rotation, fertilisation, and soil tillage on fertility and productivity, while providing essential data for developing sustainable solutions adapted to the pedoclimatic conditions of the Republic of Moldova and Romania (Figure 2).



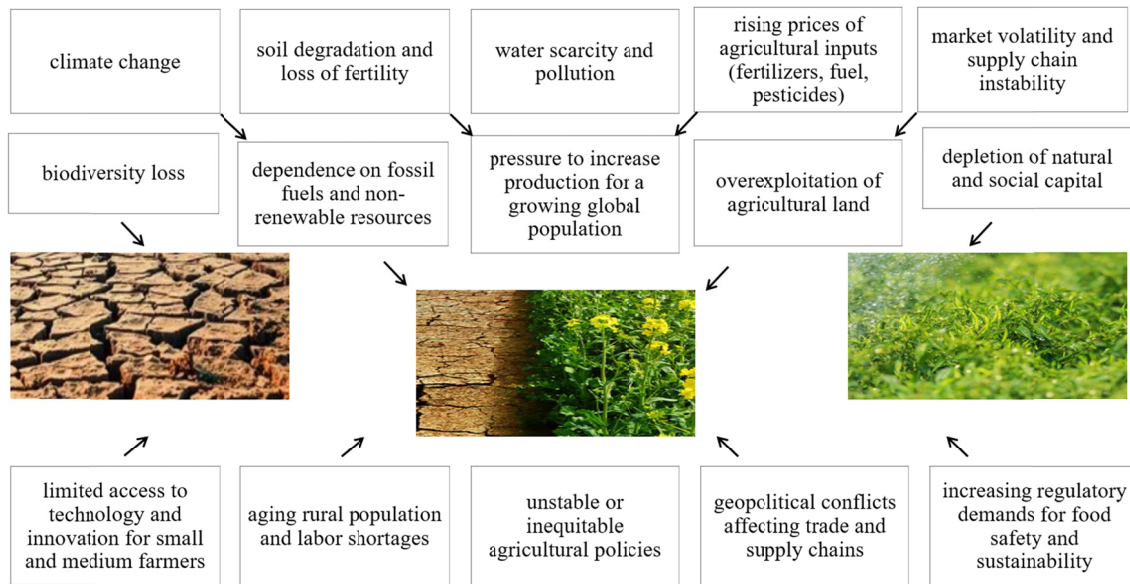
**Fig. 2. Methodology and Working Methods of the Long-Term Experiment.**

### 3. Conceptual Framework.

Agriculture significantly impacts the environment and climate change, accounting for between 16% and 37% of global greenhouse gas emissions with degradation of ecosystems, water resources, soil and biodiversity (Adedibu, 2023; Crippa et al., 2021; Ekka et al., 2023) (Figure 3).

The latter has contributed to destabilising markets (for cereals and fertilisers), an aspect that has revealed the fragility of global supply chains and dependence of industrial agriculture on external resources (Ben Hassen & El Bilali, 2022; Khatri et al., 2024; Kozielec et al., 2024). The vulnerability of agriculture is amplified by price volatility, especially in relation to production factors, such as fossil fuels and mineral fertilisers.

In this context, soil degradation has reached alarming proportions, estimated to affect over one-third of agricultural land, and climate crises (prolonged droughts or frequent floods) compromise the stability of agricultural production (Hamulczuk et al., 2023; X. Li et al., 2023). Some countries, especially those facing acute climate challenges, have begun to move towards agricultural policies oriented towards solutions based on digital technologies and smart sensors to better and efficiently manage limited resources (Ghosh et al., 2025; Narayanan et al., 2025). Data indicate that approximately 90% of farmers are already affected by water scarcity, and over 60% are willing to adopt advanced agricultural technologies to optimise resource consumption and increase land productivity.



**Fig. 3. The Main Global Pressures on Agriculture.**

Integrating advanced digital technologies (agritech) into agriculture creates new opportunities to rationalise resource use and reduce dependence on expensive and polluting industrial inputs. (Jabbari et al., 2023, 2024) Real-time monitoring of agricultural soil data and advanced sensors increases application rates and reduces chemical consumption without compromising yields. Thus, agritech improves production efficiency and offers a sustainable response to modern agriculture's economic and environmental challenges (Carvalho et al., 2025; Nehrey & Zomchak, 2022).

Thus, agricultural intensification and short-term production maximisation are becoming less and less out of step in a context marked by climate, economic, and social crises. The focus is shifting towards emerging solutions for more circular, regenerative, and energy-efficient agriculture, which requires institutional coordination, support for farmers, and political engagement.

### **3.1. The European Policy Shift in Agriculture.**

At the European Union level, agriculture has enjoyed accelerated intensification in recent decades. Despite temporary productivity increases, this intensification model has come with environmental, social, and economic costs that are hard to ignore.

The latter have contributed enormously to biodiversity decline, soil degradation, water pollution, and increased dependence on fossil fuels and synthetic fertilisers (Levers et al., 2016; Staniszewski et al., 2023). This model is also particularly vulnerable to climate, energy, and geopolitical crises. Significant price increases have raised pressure on farmers and exposed the vulnerabilities of systems based on non-renewable resources (Moersdorf et al., 2024).

In this context, it is becoming increasingly clear that traditional intensification is no longer the basis for sustainable agriculture over the long term. In response, the European Union has started encouraging a transition towards sustainable intensification by promoting policies that capitalise on the principles of the circular economy and agroecology (Figure 4).

Strategies such as Farm to Fork (European Commission, 2020) and the EU Soil Strategy for 2030 (European Commission, 2021) propose the adoption of strategies that drastically reduce nutrient losses, reduce resource consumption, and restore the natural capital of soils and ecosystems. The common point of these strategies converges toward promoting a transition to circular agriculture (O'Keeffe et al., 2025). However, implementing such a model on a large scale is challenging.



**Fig. 4. Key Aspects of the Transition to Circular Agriculture in Europe.**

Among the latter, the most important are the socio-economic disparities between large and small farms, unequal access to technological innovations, the bureaucracy of European funds, and the lack of agricultural training integrated into the new ecological paradigms that limit the transition.

Thus, the future of agriculture is closely correlated with the ability to rethink intensification not as a simple increase in production, but as a systemic strategy aimed at regenerating agricultural ecosystems, capitalising on local resources, and restoring the balance between productivity, social equity, and environmental health (Matysik-Pejas et al., 2023; Peng et al., 2025; Velasco-Muñoz et al., 2021).

Regarding the transformations needed for circular and sustainable agriculture, the circular economy is emerging as a strategic framework that closes resource cycles and reduces ecological impact. It adapts differently at the level of European countries, in accordance with national specificities, existing infrastructure, and political support. The Netherlands is a leader in applying the circular economy in agriculture. The national strategy (adopted in 2016) foresees transforming the entire economy into a circular system by 2050, with agriculture as a priority sector.

Agricultural systems have been developed to valorise organic waste (including manure and plant residues) into fertilisers, minimise nutrient losses, and integrate bioenergy flows into mixed farms. The challenges faced by this country particularly call for the complexity of logistics and the investments needed for digitalisation and automation (K. Khan & Khurshid, 2024; Matysik-Pejas et al., 2023).

In the move towards circular agriculture, however, there are challenges here too; they refer to the lack of collaboration among traditional farmers and the difficulty of harmonising regulations regarding organic waste in the agricultural context (Castillo-Díaz et al., 2024; De Jesus & Aguiar Borges, 2024; Sørensen et al., 2025).

Another shade of adopting circular economy principles is applied in Finland's agriculture through strategies that support biogas production, soil conservation, and crop rotation with plant cover. The advantage of this model lies in the constant government support and close partnership between various public and private partners. At the same time, the disadvantages are limited to the challenging climatic conditions for certain types of crops and the availability of biomass for internal recycling (Aarikka-Stenroos et al., 2023; Marttila et al., 2024).

Austrian agriculture is distinguished by balancing modernisation and traditional regenerative practices (Brumer et al., 2023; Erdiaw-Kwasie et al., 2025; Vranjanac et al., 2025; Yang et al., 2024).

Therefore, although the transition to circular agriculture has various forms of implementation in Europe, a common denominator remains the importance of the legislative framework, applied research, and cooperation between the agricultural, energy, and environmental sectors. These examples show that the success of such a transition does not depend exclusively on the available technologies, but especially on the adaptability of local agricultural systems, farmer education, and economic incentives oriented towards sustainability.

### **3.2. Agricultural Intensification in Romania and Republic of Moldova.**

The transition to a circular agri-food model in Romania and the Republic of Moldova reflects emerging concerns at the European level regarding sustainable reconstruction of the food system. Some of the most significant principles of CE that are intended to be introduced, but are still in their early stages, call for reducing resource waste, closing material loops through recycling and composting, and valorising organic waste (Stratan et al., 2024; Vajda et al., 2025). European projects and independent initiatives partly supported Romania's transition to circular agriculture. An example is adopting small-scale composting practices as an alternative to mineral fertilisers. These practices promote the transformation of agri-food waste into valuable bioproducts (biofertilisers or biopesticides), in line with European strategies for the bioeconomy (Cioca et al., 2021; Vajda et al., 2025). However, the practical application of circular economic principles to conventional agriculture is limited. These limitations are due to the lack of composting infrastructure, the fragmentation of agricultural holdings, and a weak applied research capacity in the bioeconomy. In addition, economic and informational barriers among farmers limit accessibility and the transition to a circular economy (Cioca et al., 2021; Jitäreanu et al., 2022).

In the Republic of Moldova, green transition commitments explicitly include the agri-food sector as a priority area (Popa et al., 2023). This strategy promotes the closure of the nutrient cycle by reusing treated sewage sludge and compost in agriculture. These interventions aim to reduce the pressure on water resources and integrate the principle of waste as a resource, which aligns with the European standards for water reuse in agriculture (Leah, 2015). Promoting biofertilisers and local renewable sources of plant nutrition is an important pillar of the transition of the Republic of Moldova, especially in an effort to reduce dependence on imported industrial inputs.

This aspect is especially relevant in the context of increasing viability by partially replacing synthetic fertilisers with composts and local biochar, without compromising productivity, but with beneficial effects on soil structure and microbial biodiversity (Boincean et al., 2016). However, the widespread implementation of the circular economy in Moldovan agriculture faces challenges similar to those in Romania: lack of infrastructure, a coherent biodegradable waste collection system, a low level of agricultural education in rural areas, and limited access to circular technologies. In both contexts, circular economy initiatives are significantly supported by European funding and international partnerships rather than by robust and well-coordinated domestic policies.

### **3.3. The Interplay between Regenerative Agriculture and the Circular Economy.**

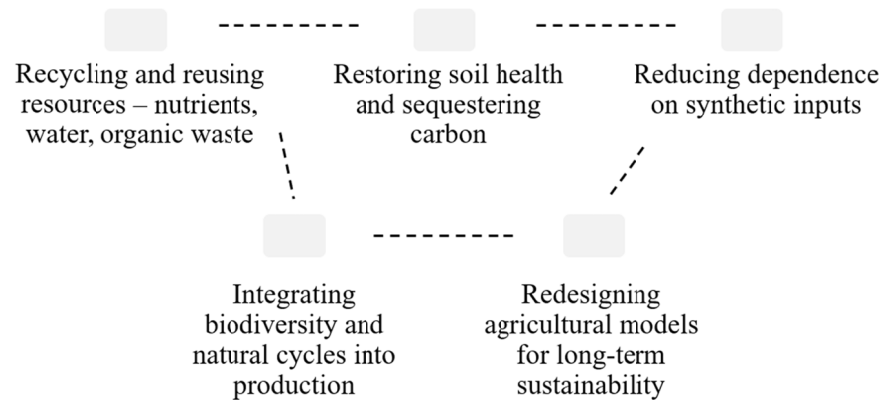
Regenerative agriculture aims to restore soil health, diversify crops, and increase biodiversity (Dent & Boincean, 2021). For example, composting plays a key role in a regenerative economy, as fertilisers derived from waste can significantly reduce reliance on inorganic nutrients such as nitrogen and phosphorus, thereby maintaining soil quality (Cordeiro & Sindhøj, 2024). Combining regenerative and circular economy principles can enable the transition to sustainable agriculture. Both paradigms aim to reduce waste, regenerate natural resources, and optimise ecological cycles.

However, they provide a complex operational framework capable of transforming current agricultural systems from extractive models into restorative, balanced, and resilient systems (Figure 5).

Crop rotation is essential because it restores soil fertility and reduces the need for synthetic fertilisers. Furthermore, nutrient recovery through composting directly reduces stress on ecosystems (Tamburini et al., 2020).

An integrated approach that includes crop rotation can improve soil structure and reduce greenhouse gas emissions by recycling organic nitrogen (Cordeiro & Sindhøj, 2024; O' Keeffe et al., 2025).

Furthermore, a cyclical approach can improve the efficiency of processing agricultural waste to produce biogas, compost, and biofertilizers (Haque et al., 2023), all of which are value-added products.



**Fig. 5. Essential Aspects of the Interaction between Regenerative Agriculture and the Circular Economy.**

Cover crops increase organic matter, stimulate microbial activity and prevent nutrient loss. Thus, covering crops support soil fertility in the long term and align with the circularity and regenerability requirements for restructuring the agricultural system (Birgovan et al., 2024; Scavo et al., 2022). Integrating crop and livestock farming is another fundamental strategy for farms that applies both principles.

In this agro-zootechnical model, organic waste generated by animals is transformed into valuable resources for soil fertilisation, while fodder crops are reintegrated into the production circuit (Montgomery & Biklé, 2015; Soto-Gómez, 2024). To ensure the ecological footprint is minimised, organic waste, straw, leaves, and even wastewater can be used and converted into compost, or biogas (Marques et al., 2025; Mengqi et al., 2023).

This approach generates multiple benefits, including soil health, reduced fossil fuel consumption and emissions, and strengthened agroecosystem resilience. (Papakonstantinou et al., 2024).

### 3.4. The Pillar of Circular Agriculture - Crop Rotation.

Crop rotation can improve soil health, biodiversity, and resource efficiency. At the same time, temporal diversification facilitates natural nutrient cycles, inhibits diseases and pest harbourage, contributes to organic matter growth, and enhances soil microbial diversity (Selvan et al., 2023; Shah et al., 2021). Diversified rotations also enhance carbon dioxide storage in arable soil, contributing to the mitigation of the effects of climate change without compromising agricultural productivity (Boincean & Dent, 2019a; Costa et al., 2024).

In addition, crop rotation contributes to the natural and sustainable control of diseases and pests by interrupting their biological cycles, thus reducing dependence on synthetic pesticides and fungicides. Crop rotation has been established as an essential strategy in the transition to sustainable agri-food systems, in which natural resources are used responsibly and ecosystems are preserved in the long term (Lugato et al., 2021; Rui et al., 2022).

## **4. Results and Discussions.**

### **4.1. Reflections on the History and Systemic Limits of Agricultural Intensification.**

The historical processes of agricultural intensification have significantly impacted the development of modern agriculture. One of the significant causes of degradation in contemporary agriculture is the separation of agricultural disciplines, which has led to isolated practices that do not reflect the complexity of farm production systems (Boincean & Dent, 2019a).

Industrial interests have favoured this approach and are often supported by public policies, promoting a mechanistic view of nature and an exaggerated trust in the ability of technology to solve any resource limitation. Throughout history, theoretical perspectives on plant nutrition have profoundly influenced agricultural practices. Liebig (1863) emphasised the importance of crop rotation, including perennial legumes, and the use of manure to restore soil fertility. Tillage does not add nutrients but only makes them available, and cannot restore soil fertility without a constant supply of organic matter.

Healthy soils with high humus content can increase crop resistance to disease, thereby protecting them (Boinssen & Dent, 2019b; Liebig & Blayfair, 2024; Liebig, 1863). Furthermore, soil health directly impacts the entire food chain, the integrity of which, in turn, depends on the integrity of agricultural systems (Goldner et al., 2021; Lal, 2009).

Rhizosphere fungi and bacteria are essential mediators between plants and nutrients, being able to absorb up to 90% of the applied phosphorus, thus contributing to the natural resistance of crops (Boincean & Dent, 2019b; Havelka et al., 1982; Khan et al., 2007). Therefore, agricultural intensification contributes to soil fertility degradation and biodiversity reduction. Re-evaluating ecological principles by favouring natural nutrient cycles and shifting the emphasis to crop rotations are essential conditions for truly sustainable agriculture (Boincean & Dent, 2019a; Kirschenmann, 2010).

### **4.2. The Effect of Fertilisation and Crop Rotation.**

The results obtained from long-term field experiments can often be misinterpreted, especially when they indicate a higher efficiency of mineral fertilisers in monoculture than in crop rotation systems. This apparent efficiency is, in reality, determined by the weakening of the root system of continuously cultivated plants, which limits their ability to absorb nutrients and water from the soil (Papakonstantinou et al., 2024).

In monoculture, the dominance of pathogenic fungi in the soil microbial community contributes to the faster degradation of the root system, especially in the case of permanent crops such as winter wheat and other species. In the long term, fungal microorganisms dominate bacterial microorganisms in permanent winter wheat crops, negatively affecting soil health and plant resilience (Bateman & Kwaśna, 1999; Hilton et al., 2018; Sharma-Poudyal et al., 2017).

The high efficiency of mineral fertilisers can mask the shortcomings of imperfect crop rotation. Instead of improving the diversity of main and cover crops for better nutrient recycling and an increased capacity of the agroecosystem to control weeds, pests, and diseases, many farmers choose to increase the doses of fertilisers and pesticides (Grzebisz et al., 2022; Shiferaw et al., 2011).

The better the crop rotation design, the lower the additional efficiency of chemical fertilisation (Table 1). Conversely, the more deficient the rotation, especially in monoculture systems, the more efficient the mineral fertilisers and, implicitly, pesticides are in the context of weaker control of weeds, diseases, and pests. Excessive fertilisation reduced the difference between the yields obtained in rotational and monoculture systems (Table 2).

This relationship was consistently confirmed for all crops studied in long-term experiments conducted at the Field Crops Research Institute Selecția in Bălți of the Republic of Moldova (2024).

**Table 1. The Effect of Crop Rotation on Winter Wheat after Different Predecessors on Fertilised and Unfertilised Plots, 2020–2024**

Crop rotations, permanent cropping	Fertilisation	Yields, t/ha						Effect of fertilisation	
		2020	2021	2022	2023	2024	Average for 2020-2024	t/ha	%
Winter wheat after mixture of vetch and oats for green forage									
Crop rotation	Unfertilised	3.48	3.76	3.67	4.53	2.51	3.59	+0.31	8.6
	Fertilised	4.02	2.49	3.49	5.99	3.58	3.90		
Winter wheat after corn for silage									
Crop rotation	Unfertilised	4.84	3.98	2.61	4.91	2.28	3.00	+0.54	18.0
	Fertilised	2.10	3.71	3.38	5.54	2.98	3.54		
Winter wheat after corn for grain									
Crop rotation	Unfertilised	1.83	5.39	1.16	3.89	1.98	2.85	+0.51	17.9
	Fertilised	2.19	4.58	2.42	4.75	3.36	3.36		
Permanent cropping of winter wheat									
Permanent cropping`	Unfertilised	1.49	2.34	0.91	2.79	1.38	1.78	+0.74	41.6
	Fertilised	1.80	2.82	0.91	5.76	1.33	2.52		

*Note: data are from long-term experiments conducted at the Field Crops Research Institute Selecția in Bălți, Republic of Moldova (2024).*

**Table 2. Winter Wheat Yields after Different Predecessors on Fertilised and Unfertilised Plots, 2020–2024.**

Crop rotations	Fertilization	Yields, t/ha						Effect of crop rotation	
		2020	2021	2022	2023	2024	Average	%	
Winter wheat after mixture of vetch and oats for green forage									
Crop rotation	Unfertilised	1.99	1.42	2.76	1.74	1.13	1.81	50.4	
	Fertilised	2.22	-0.33	2.58	0.23	2.18	1.38		35.4
Winter wheat after corn for silage									
Crop rotation	Unfertilised	0.35	1.64	1.70	2.12	0.9	1.22	40.7	
	Fertilised	0.30	0.89	2.47	-0.22	0.53	1.02	28.8	
Winter wheat after corn for grain									
Crop rotation	Unfertilised	0.34	3.05	0.25	1.10	0.6	1.07	37.5	
	Fertilised	0.39	1.76	1.51	-1.01	1.52	0.84	25.0	

*Note: data are from long-term experiments conducted at the Field Crops Research Institute Selecția in Bălți, Republic of Moldova (2024).*

### 4.3. The Role of Lucerne and Organic Fertilisers in Agriculture.

Lucerne, grown either alone or in a mixture with perennial grasses, is key in improving nutrient and energy recycling in agroecosystems, especially when integrated into crop rotations with compost from fermented manure.

Data from a long-term experiment conducted between 2021 and 2024 showed that the additional application of mineral fertilisers did not provide significant benefits when compost was already used in rotations that included perennial plants. In other words, chemical fertilisers did not increase the yield in organically fertilised systems (Table 3).

**Table 3. Winter Wheat Yields in Ecological Crop Rotations with and Without Annual-Perennial Herb Mixtures, 2021–2024.**

Unfertilised					Farmyard manure (compost)					Farmyard manure + PK					Farmyard manure + NPK							
2021	2022	2023	2024	Average	2021	2022	2023	2024	Average	± to unfert.	2021	2022	2023	2024	Average	± to farmyard manure	2021	2022	2023	2024	Average	± to farmyard manure
Winter wheat after mixture of legumes (alfalfa) and grasses. 3-rd. year after first cutting																						
4.23	1.92	4.48	2.82	3.36	2.99	1.54	4.91	2.80	3.06	-0.30	2.83	1.64	5.10	2.59	3.04	-0.02	3.14	1.80	4.67	2.56	3.04	-0.02
Winter wheat after mixture of annual vetch and oats for green forage																						
4.12	2.16	4.02	1.92	3.06	4.37	1.95	5.80	2.20	3.58	+0.52	3.18	2.08	5.92	2.75	3.48	-0.10	3.93	1.71	5.63	2.42	3.42	-0.16

In rotations based on annual crops, where mixtures of plants such as spring vetch and oats were used as green manure for winter wheat, in combination with compost, a yield increase of +0.52 t/ha was obtained compared to unfertilised variants. However, when mineral fertilisers were also applied to soils already fertilised with compost, wheat yield decreased by 0.10–0.16 t/ha, indicating an adverse effect of additional fertilisation. Similar results were observed in another complex long-term experiment, which analysed

the interaction between crop rotation, soil tillage systems, and organic fertilisation without chemical pesticides or herbicides. The highest yield of winter wheat (3.84 t/ha) was recorded in the rotation, including a mixture of alfalfa and ryegrass, combined with an alternation between classical ploughing and minimal soil tillage. The application of compost slightly increased the yield (3.92 t/ha), but adding mineral fertilisers, on top of compost, again led to a reduction in yield (3.7 t/ha), as shown in Table 4.

**Table 4. The Yield of Winter Wheat (Variety Talisman) in the Polyfactorial Experiment, Average for 2020-2023, t/ha.**

Variant	Alternation of mouldboard plough and non-inversive tillage	Non-inversive tillage
Crop rotation with the mixture of perennial grasses		
1	3.84	2.88
2	3.92	3.27
3	3.70	3.18
Crop rotation without perennial herbaceous crops		
1	2.40	2.30
2	3.08	3.15
3	3.45	3.15

In the systems with minimal tillage and perennial crops, winter wheat yield was lower by 0.96 t/ha in the unfertilised plots. However, the positive influence of compost was manifested by an increase of +0.35 t/ha in the compost treatment. In this case, additional fertilisation with mineral fertilisers did not provide any benefits.

#### **4.4. Agroecology in Ensuring Sustainable Development.**

The growth of the global population requires a more efficient use of essential resources, such as energy, water, soil, and genetic diversity. An increasing number of researchers argue that agroecology is the only viable solution to ensure the feeding of the global population in the context of depletion of natural resources, growing demand for food, and climate change (Gliessman et al., 1998).

It is important to realise that sustainable agriculture offers much more than food. It contributes significantly to consolidating the natural and social capital. These aspects are difficult to quantify but are essential for long-term stability. A sustainable agroecosystem maintains its resource base, uses a minimum of artificial external inputs, manages pests and diseases through internal regulatory mechanisms, and can regenerate after disturbances caused by agricultural work.

In other words, agricultural systems should mimic the functions of natural ecosystems. This implies high biodiversity along the entire food chain, both above and below the ground. A current example of the transition to agroecology is the widespread adoption of conservation agriculture in the Republic of Moldova and Romania.

This alternative agricultural system is based on the simultaneous observance of three fundamental principles: reducing mechanical soil work through direct sowing, maintaining soil cover with plant residues or cover crops (live or dead mulch), and crop diversification within rotations. Many Moldovan farms that correctly apply these principles have achieved remarkable results. However, the results were not as expected when no-till technology was adopted without adequate rotations and sufficient cover crops or residues.

In such cases, farmers faced several problems related to weeds, pests, diseases, or nitrogen deficiencies, and were forced to abandon the system. Therefore, farmers are supported in workshops, as previously, specialised disciplines have focused exclusively on cultivation technology without considering its impact on the entire food chain. More than half of all energy consumed in the food system goes into food distribution (Pimentel et al., 2010), and up to a third of food is lost (Lal, 2001).

Thus, analysing the life cycle of food products is essential for optimising energy consumption. Reducing the distance between the producer and consumer can significantly contribute to solving problems related to food security, resource efficiency, and environmental protection. Pretty et al. (2025) stated that similar principles suggest the integration of ecosystem functions into the ecological management system. Another direction is to minimise the use of non-renewable inputs, which are harmful to the environment and health, and to capitalise on the knowledge and skills of farmers, thus replacing dependence on external resources with human capital. Moreover, another direction of action is to use local cooperation to manage natural resources and common problems, such as pest control, irrigation, forests, or credit systems.

#### **5. Conclusions.**

The current model of agricultural intensification, based on the intensive use of non-renewable energy sources and a reductionist approach, no longer adequately responds to the economic, ecological, and social challenges of contemporary agriculture. The fragmentation of scientific knowledge and separation of agricultural disciplines have led to isolated practices, oriented towards immediate effects and often supported by industrial interests, with an emphasis on maximising short-term production to the detriment of the ecological functioning of agroecosystems. This model has favoured soil degradation, decreased biodiversity, and increased dependence on mineral fertilisers and pesticides, especially in monoculture systems.

Adequate chemical fertilisation in monoculture masks the deficiencies of crop rotation and the weakening of the plant root system. Under well-designed rotations, the additional effect of chemical fertilisation is significantly reduced, whereas in monoculture, the dominance of pathogenic fungi and microbiological imbalance amplify the vulnerability of crops. Experiments with alfalfa and compost clearly showed that the additional application of mineral fertilisers sometimes even decreases production (−0.10–0.16 t/ha), confirming the importance of organic fertilisation and the integration of perennial plants for restoring fertility. Resource recycling and built-in pest and disease control mechanisms are the cornerstones of sustainable agricultural development.

Implementing circular economy principles, engaging innovative farmers, and training new generations of agronomists are key to competitive agriculture that can respond to current and future challenges without compromising natural and social capital.

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