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Role of crop rotation in sustainable farming: Enhancing soil health, productivity, and environmental sustainability

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Abstract

Crop rotation is one of the main farming practices that contribute to the development of agricultural sustainability in many ways, especially through enhancing soil fertility, raising agricultural productivity, and minimizing environmental degradation. This research aims at assessing the role played by crop rotation in achieving agricultural sustainability based on the study of different farming models and secondary data obtained from previous agricultural research. It is noted that farmers who adopted a farming system involving 3-year and 4-year crop rotations experienced a rise in crop yields ranging between 18% and 32% when compared to monoculture agriculture. The quantity of organic matter in soil increased by 12%, while the availability of soil nitrogen rose by almost 25% owing to leguminous crops, like beans and pulses. Crop rotation contributed to the decrease in the rate of weeds, pests, and plant diseases by 28%, 35%, and 30%, respectively, which minimized the need for pesticides in the process. Besides, water retention capacity was found to have increased by 15%, which helped improve soil drought tolerance and irrigation efficiency. Economically, farmers engaged in crop rotation were able to minimize their cost inputs by 20% while experiencing a rise in net income of about 17%. This paper has shown that crop rotation is a viable, inexpensive, and sustainable approach that is able to sustain food security, adaptation to climate change, and farm profitability in the long run. This would be achieved through scientific rotation plans, government policies, and farmers' education programs.

Keywords: Crop rotation, sustainable farming, soil fertility, agricultural productivity, pest management, biodiversity, water conservation, climate resilience, farm profitability, organic agriculture

Introduction

Sustainable agriculture is of global importance due to growing human demand, dwindling resources, climate change and the need for sustainable food production. Traditional agricultural practices and systems that rely on monocropping and heavy use of fertilizers and chemicals have boosted productivity over the last few decades, but they have also led to soil degradation, loss in biodiversity, depletion of nutrients, and emission of greenhouse gases (Joshi *et al.*, 2021; Mesele *et al.*, 2025) ^[3, 23]. In this regard, scientists and policymakers are turning their attention to ecological farming systems that ensure productivity without compromising the environment. Crop rotation is one of the most feasible and affordable approaches to sustainable agriculture (Freyer, 2025; Zou *et al.*, 2024) ^[1, 19]. Crop rotation is the systematic planting of various crops in a field over several years or growing seasons. In contrast to monocultures, which involve growing a single crop year after year, rotation systems involve growing a diverse range of plant species and result in a balanced nutrient recycling, enhanced soil structure, and natural pest and disease control (Bhatt *et al.*, 2023; Wesołowska *et al.*, 2022) ^[9, 43]. Crop rotation was historically practised by traditional farmers in Asia, Africa and Europe before the advent of fertilizers. In the present era of scientific farming, crop rotation is a key component of regenerative and climate-smart agriculture (Nawaz *et al.*, 2024; Kumar *et al.*, 2024) ^[10, 13]. Crop rotation plays a crucial role in improving soil fertility and nutrition. Variations in nutrient requirements and root architecture of the different crops allow soil to rest in scientifically designed crop sequences. Legumes like soybean, peas, lentils and clover have the ability to fix atmospheric nitrogen with the help of symbiotic bacteria, and make the soil fertile for cereal crops (Iahtisham-Ul-Haq &

Shahid, 2025; Mrunalini *et al.*, 2022) [5, 34].

Longterm rotation studies have demonstrated improved nitrogen-use efficiency, soil organic carbon content and nutrient cycling with legume inclusion in crop rotation (Denardin *et al.*, 2025; Panagea *et al.*, 2025) [18, 26]. Crop rotation also plays a significant role in soil physical properties. Continuous cropping of the same crop can result in soil compaction, reduced aeration, and water penetration. Crop rotation cycles involving deep-rooted crops, cover crops and forage crops enhance soil structure, stability and water retention (Tarafdar, 2022; Rossi *et al.*, 2024) [17, 49]. Research in organic agriculture also suggests that rotation influences soil organic matter dynamics, which is crucial for long-term sustainability and drought resilience (Murindangabo *et al.*, 2025; Laila *et al.*, 2024) [41, 47]. Crop rotation is also significant in pest, weed and disease control. Crop monoculture provides a suitable habitat for pests and pathogens to evolve and specialise on a single host. Sequencing different crop species breaks the life cycle of insects, nematodes, fungi and weeds, thereby reducing pest pressure (Du *et al.*, 2025; Kohli *et al.*, 2024) [28, 31]. This natural process reduces the need for chemical pesticides and herbicides, reducing production costs and harmful effects on the environment (Freyer, 2025; Seimandi-Corda *et al.*, 2026) [1, 52]. Enhancement of biodiversity is another key benefit of crop rotation systems. Modified crop rotation sequences attract unique microbial, insect, pollinator, and other soil fauna, enhancing biodiversity. Studies have demonstrated that crop diversification increases bacterial diversity, earthworm population and beneficial microbiome activity compared to monocultures (Bhatt *et al.*, 2023; Ligrone *et al.*, 2024; Giménez *et al.*, 2025) [6, 37]. Increased biodiversity helps in nutrient cycling, pest suppression, and ecosystem stability in croplands (Brito *et al.*, 2021) [11]. Crop rotation has tangible economic advantages for farmers in terms of reducing the risk of crop failure and input costs. While monoculture is considered easy and lucrative, long-term experiments show that rotation systems often yield greater stability of income by reducing the cost of fertilizers, insecticides, and irrigation while increasing yield over time (Riar *et al.*, 2025; Raghavendra *et al.*, 2025) [25, 42]. In rainfed and marginal areas, rotational systems have also led to increased productivity of millet, ricewheat, and maize-soybean systems (Bado *et al.*, 2022; Bai *et al.*, 2025; Dabessa & Debala, 2023) [14, 20, 46]. The need for sustainable farming has become more urgent with climate change. Increasing temperatures, rainfall variability, floods and droughts affect global food production. Crop rotation enhances resilience through risk diversification, water-holding capacity and reduced reliance on external chemical inputs, whose production has a carbon footprint (Salman Chowdhury *et al.*, 2025; Nawaz *et al.*, 2024) [21]. Legume and cover crops in rotation can also reduce greenhouse gas emissions and increase carbon storage (Valujeva *et al.*, 2025; Madjar *et al.*, 2025) [33, 45]. Crop rotation can have a profound impact on food security and livelihoods in developing nations, particularly in Asia and Africa. They experience soil fertility decline, high input costs and climate change. Crop rotations based on cereals, pulses, oilseeds and fodder can improve yields and mitigate risks (Joshi *et al.*, 2021; Mesele *et al.*, 2025). However, its uptake relies on extension support, market access, availability of quality seed, and farmers' knowledge. Crop rotation is also being enhanced by technology. New technologies such as artificial intelligence, remote sensing, and precision agriculture can help farmers to plan crop sequences using soil and weather information, pest and price forecasts (Mahmood *et al.*, 2024; Zhu *et al.*, 2024) [27, 51]. This

technology can digitise traditional rotational knowledge into sustainable farming systems fit for scaling up. Despite the advantages, there are still challenges in adopting crop rotation. These include short-term financial gains, policy incentives for monocultures, small land-holdings and a lack of technical expertise. Lack of storage and marketing infrastructure for rotational crops such as pulses or forage crops in some areas discourages crop rotation (Grace *et al.*, 2025; Solovieva *et al.*, 2025) [29, 32]. So institutional support and policy changes are needed to facilitate adoption. This research paper will explore the role of crop rotation in sustainable agriculture by assessing its effects on soil fertility, crop yield, biodiversity, climate change and farm income. It also discusses the limitations and potential solutions for incorporating crop rotation into agricultural practices. Understanding these dimensions is crucial for building resilient food systems capable of meeting future global demands while protecting environmental resources (Freyer, 2025; Zou *et al.*, 2024; Kumar *et al.*, 2024) [1, 19, 13].

Background of sustainable agriculture

Sustainable agriculture has emerged as a holistic approach to address the environmental, economic and social problems arising from intensive agricultural production. While the Green Revolution era saw a dramatic increase in agricultural productivity with high-yield crop varieties, mechanisation, fertilizers, and pesticides, this was often at the expense of soil health, biodiversity loss, water quality, over-extraction of groundwater, and greenhouse gas emissions (Joshi *et al.*, 2021; Mesele *et al.*, 2025) [3, 23]. Sustainable agriculture aims to achieve both productivity and environmental sustainability through agricultural practices that sustain soil fertility, conserve water, minimize pollution, increase biodiversity, and enhance economic profitability over time. It aims to make optimal use of natural resources, while avoiding excessive use of non-renewable inputs and environmentally damaging chemicals (Freyer, 2025; Kumar *et al.*, 2024) [1, 13]. Key sustainable farming practices include crop rotation and diversification, nutrient cycling and balanced fertility inputs, minimum tillage, organic matter amendments, biological pest management, and climate-resilient farming systems (Nawaz *et al.*, 2024; Tarafdar, 2022) [10, 17]. Soil fertility is especially important for this system as healthy soils enhance nutrient dynamics, water storage, microbial functions, and crop resistance to stressors (Murindangabo *et al.*, 2025; Laila *et al.*, 2024) [41, 47]. New research also demonstrates that sustainable agriculture enhances ecosystem services (pollination, carbon storage, erosion mitigation) and enhances rural livelihoods and communities (Brito *et al.*, 2021; Cogné & Lescuyer, 2024) [8, 11]. Sustainable agriculture is increasingly recognised as critical for food security in many developing countries due to resource scarcity, land degradation and climate change, affecting smallholder farmers (Salman Chowdhury *et al.*, 2025; Dabessa & Debala, 2023) [21, 46]. Governments and international agencies now endorse sustainable policies in agriculture that include regenerative farming, organic farming, and smart farming technologies such as artificial intelligence-based resource allocation and precision nutrient management (Mahmood *et al.*, 2024; Zhu *et al.*, 2024) [27, 51]. Therefore, sustainable agriculture is not just another production system but a transition toward robust food systems that fulfil current needs while not impairing the ability of future generations to produce food and retain environmental health (Freyer, 2025; Zou *et al.*, 2024; Madjar *et al.*, 2025) [1, 19, 45].

Importance of crop rotation in farming systems

Crop rotation is one of the most ancient and scientifically proven methods of sustainable farming systems as it involves the planned rotation of different crops on the same field over several growing seasons or years to enhance ecological efficiency and yields. Crop rotation replenishes soil nutrients, breaks pest cycles, and offers diverse yields, unlike monocropping (growing the same crop over and over again), which can lead to depletion of soil nutrients, pest outbreaks, and eventually low yields (Bhatt *et al.*, 2023; Wesołowska *et al.*, 2022) [9, 43]. Crops vary in rooting patterns, nutrient uptake, and crop residues, allowing them to better use soil resources when planted in a specific order. For instance, legumes after cereals take advantage of the nitrogen fixation capacity of legumes, avoiding the use of fertilizers (Iahtisham-UI-Haq & Shahid, 2025; Mrunalini *et al.*, 2022) [5, 34]. Extended field trials have shown better nitrogen-use efficiency, increased soil organic carbon content, and enhanced nutrient cycling in rice-soybean, wheat-cotton, maize-soybean, and millet-based crop rotation systems (Denardin *et al.*, 2025; Riar *et al.*, 2025; Bado *et al.*, 2022) [14, 18, 25]. Crop rotation also improves soil structure and water-holding capacity through diverse root structures that promote soil aggregation, aeration and water retention, thus enhancing drought resistance and preventing soil erosion (Tarafdar, 2022; Rossi *et al.*, 2024) [17, 49]. Biologically, crop rotation enhances beneficial microbial communities, earthworms, and mycorrhizal symbiosis that enhance nutrient absorption and disease prevention (Ligrone *et al.*, 2024; Giménez *et al.*, 2025; Brito *et al.*, 2021) [6, 11, 37]. It is also crucial in integrated pest management as rotating crops disrupts the life cycles of insects, weeds, fungi and nematodes, reducing the need for pesticides and chemical residues (Du *et al.*, 2025; Kohli *et al.*, 2024; Seimandi-Corda *et al.*, 2026) [28, 31, 52]. From an economic perspective, crop rotation enhances production security by diversifying production and buffering yield variability through climate change and market risk (particularly important for smallholder farmers) (Joshi *et al.*, 2021; Salman Chowdhury *et al.*, 2025) [3, 21]. In climate change scenarios, rotational farming with legumes, cover crops, and forage crops aids in carbon sequestration and reduces greenhouse gas emissions, while enhancing resilience (Valujeva *et al.*, 2025; Bai *et al.*, 2025; Madjar *et al.*, 2025) [20, 33, 45]. Data-driven technologies including artificial intelligence, satellite imagery, and predictive models are also enhancing crop rotation strategies, using soil and weather data and profitability metrics (Mahmood *et al.*, 2024; Zhu *et al.*, 2024) [27, 51]. So, crop rotation still plays a pivotal role in sustainable agriculture as it combines ecological, economic, and long-term farming perspectives (Freyer, 2025; Zou *et al.*, 2024) [1, 19].

Objectives of the Study

1. To assess the effects of crop rotation on soil properties and fertility

This goal involves investigating the effects of various crop rotation schedules on soil health indicators like organic matter, nutrient levels, microbial activity, water-holding capacity and structure. Soil health is important in sustainable agriculture as it provides a foundation for long-term crop production and reduces the need for fertilizers.

2. To examine the impact of crop rotation on crop yields and farm income

The research will test if crop rotation can boost productivity, minimise disease and pest attack, and enhance farmers' profits. This study will compare the productivity of monocropping with

crop rotations to determine the most productive and profitable cropping patterns.

3. To measure crop rotation's role in improving environmental sustainability and climate resilience

This goal focuses on how crop rotation helps minimise soil erosion, greenhouse gas emissions, nutrient leaching and water scarcity, and helps adapt to drought, flood and climate change. It helps understand the environmental advantages of crop diversification in sustainable farming.

Research Questions

1. Does crop rotation impact soil fertility and life more positively than monocropping?

This question seeks to understand whether crop rotation increases soil fertility, soil microbiology and soil organic carbon (carbon stored in the soil) better than monocropping (using the same crop on the same area of land).

2. How does crop rotation affect crop productivity or farmer's income?

This question explores whether crop rotation increases production, reduces costs and increases farmer profits compared with monocultures.

3. Does crop rotation promote economic sustainability, and adaptability to climate change?

This question examines whether crop rotation helps to reduce greenhouse gas emissions, conserve water, prevent pest outbreaks, and cope with climatic change.

Hypothesis

H1: Crop rotation has a positive impact on soil fertility, compared to monocropping.

Crop species vary in their nutrient requirements and how they add nutrients to the soil, and this is likely to enhance soil fertility and humus content.

H2: Average yields in crop rotation farms are higher than in monocrop farms.

Crop rotation is anticipated to minimize pests, improve soil fertility and crop production over time.

H3: Crop rotation reduces pests, weeds and crop diseases.

Successive growing of different crop species helps prevent pests and pathogen build-up, reducing infestation.

H4: Crop rotation boosts farm income with lower costs and higher yields.

The reduction in fertiliser and pesticide inputs and the maintenance of farm yields should increase farm profits.

H5: Crop rotation helps to protect the environment and build climate resilience.

Crop rotation is anticipated to reduce erosion, retain moisture, emit less greenhouse gas and increase farm resilience to climate change.

Literature Review

Crop rotation and multi-crop systems are increasingly seen as the basis of sustainable production systems as they improve soil fertility and health, control pests, improve yield stability and

adaptability to climate change. In particular, crop rotations are a cornerstone of organic systems to sustain nutrient and biological equilibrium without chemical inputs. Thus, regional crop selection and dynamic cropping systems are crucial to the success of organic farming, with rotations tailored to local climate, soil characteristics, and market needs (Freyer, 2025) ^[1].

Studies also find that diversified rotations are more sustainable than monocultures in the long run by cutting external inputs and increasing ecosystem services (Zou *et al.*, 2024; Riar *et al.*, 2025) ^[19, 25]. The table 1 shows the Comparative Review of Sustainable Cropping Systems, Organic Farming, Soil Health, and Climate-Resilient Agricultural Practices.

Table 1 Comparative Review of Sustainable Cropping Systems, Organic Farming, Soil Health, and Climate-Resilient Agricultural Practices

Ref No.	Title	Author(s) & Year	Findings	Research Gaps	Methodology Used
1	Choice of Crops and Cropping Systems for Organic Farming in the Region	B. Freyer (2025) ^[1]	Region-specific crop selection and diversified rotations improve organic farm productivity and resilience.	Limited empirical validation across climatic zones and farm scales.	Conceptual review, case-based synthesis
2	Role of Rye in Sustainable Food Systems and Biofuel Applications	A. K. Berbeć & M. Wyzinska (2025) ^[2]	Rye supports nutrition security and renewable biofuel feedstock systems.	Need lifecycle comparisons with wheat and maize systems.	Literature review, nutritional and energy evaluation
3	Conservation Agriculture for Food Security and Climate Resilience in Nepal	D. R. Joshi <i>et al.</i> (2021) ^[3]	No-till, residue retention, and crop diversification improved yields and climate resilience.	Long-term socio-economic adoption barriers remain understudied.	Field trials, survey analysis
4	Sustainability Practices in Indonesian Cattle Farming	A. Suarsa <i>et al.</i> (2024) ^[4]	SAFA framework showed strengths in welfare and resource management.	Limited comparison with industrial livestock systems.	Sustainability assessment framework
5	Legumes Production under Changing Climate	Iahtisham-Ul-Haq & N. Shahid (2025) ^[5]	Legumes enhance nitrogen fixation and tolerate climate stress better than cereals.	Need genomic breeding for extreme weather resilience.	Review chapter
6	Seasonal Dynamics of Agricultural Land Use Impacts on Earthworm Communities	A. Ligrone <i>et al.</i> (2024) ^[6]	Intensive land use reduced earthworm diversity and abundance.	Few tropical-region comparative studies available.	Seasonal field sampling, biodiversity analysis
7	Potato Yield and Quality Linked to Cover Crop and Soil Microbiome	M. Hemkemeyer <i>et al.</i> (2024) ^[7]	Cover crops increased yield; microbial diversity improved tuber quality.	Mechanistic microbial interactions still unclear.	Experimental plots, microbiome sequencing
8	Agroforestry Contribution to Well-being in Timor-Leste	M. Cogné & G. Lescuyer (2024) ^[8]	Agroforestry improved income, food access, and livelihood resilience.	Scaling barriers and policy incentives need study.	Household surveys, livelihood analysis
9	Crop Rotation on Bacterial Diversity and Soil Quality	M. Bhatt <i>et al.</i> (2023) ^[9]	Rotations significantly improved bacterial diversity and soil fertility under organic systems.	Lack of multi-year microbial monitoring.	Soil sampling, microbial assays
10	Climate Change-Resilient Crop Production	T. Nawaz <i>et al.</i> (2024) ^[10]	Stress-tolerant crops and adaptive agronomy reduce climate risks.	Need region-specific adaptation packages.	Review chapter

A number of studies show crop rotations enhance soil physical, chemical and biological properties. Crop rotations with cereals, legumes and oilseeds show greater soil organic matter content, aggregate stability and microbial diversity compared to monocultures (Bhatt *et al.*, 2023; Wesołowska *et al.*, 2022) ^[9, 43]. Soil organic matter is important in organic systems, where crop residues and rotations help to sequester carbon and nutrients (Murindangabo *et al.*, 2025) ^[47]. Sustainability indicators and soil quality are also enhanced through long-term no-tillage with stubble retention in forage-crop rotations grown under rainfed conditions (Dong *et al.*, 2025) ^[24]. Legume rotations are often seen as key systems in reducing nitrogen fertiliser use due to their nitrogen-fixing abilities. Grain legumes are recognised as climate-smart crops that can sustain productivity under adverse conditions and improve soil fertility (Krishna, 2025) ^[12]. However, forage and grain legumes can have different effects on soil organic carbon (SOC) stocks depending on biomass returned and management practices (Panagea *et al.*, 2025) ^[26]. Under climate-smart practices, legumes play an important role in reducing ecological footprints, increasing nutrient use efficiency and enhancing crop productivity in rotation (Mrunalini *et al.*, 2022; Iahtisham-Ul-Haq & Shahid, 2025) ^[34, 5]. In rice-soybean rotations, the integration of livestock and rotation also increased nitrogen use efficiency in paddy fields (Denardin *et al.*, 2025)

^[18]. The other prominent theme in the studies reviewed is climate change adaptation. Crop rotations enhance resilience by spreading risk, conserving water, and mitigating extreme weather events. In Nepal, conservation farming practices such as less tillage, crop residue retention and diversification increased farmers' climate resilience and food security (Joshi *et al.*, 2021) ^[3]. Similar results were found in water-scarce Bangladesh, where farmers increasingly practised crop diversification and adaptive management in response to climate change (Salman Chowdhury *et al.*, 2025) ^[21]. Resilient crop production also requires integration of improved varieties and water-saving technologies, and resilient crop rotations (Nawaz *et al.*, 2024) ^[10]. Crop diversification is also promoted by sustainable intensification research for improving productivity while reducing environmental impacts. In the West African Sahel, millet-based diversified systems in the long-term improved yields and resource-use efficiencies under low-input scenarios (Bado *et al.*, 2022) ^[14]. In Ethiopia, soybean-maize rotation trials also demonstrated the superiority of rotational systems over cereal monocropping systems due to improved nutrient cycling and yield stability (Dabessa & Debala, 2023) ^[46]. In India, cotton-based systems with wheat and soybean rotations noted positive economic and yield results in organic and conventional systems (Riar *et al.*, 2025) ^[25]. These studies highlight the importance of

rotation for productivity and sustainability. Soil biology has taken centre stage in rotation studies. Soil biology plays a critical role in nutrient dynamics, disease control and productivity (Tarafdar, 2022) [17]. Incorporating cover crops into rotations can enhance microbial populations and yields, such as potato production where yield and quality were associated with cover crops and soil microbiome (Hemkemeyer *et al.*, 2024) [7]. Comparing croplands and natural grasslands, intensive farming resulted in loss of microbial diversity, so there is a need for regenerative rotations to recover microbial functions (Giménez *et al.*, 2025) [37]. Beneficial arbuscular mycorrhizal fungi are also deemed important for sustainable crop intensification (Brito *et al.*, 2021) [11]. The positive effects of rotation on weed, pest and disease control are well reported. Diversity in rotation disturbs pest and pathogen cycles, thereby decreasing pesticide use. The role of the microbiome in plant disease resistance is also becoming important as microbes associated with diversified systems can suppress pathogens and boost plant defences (Du *et al.*, 2025) [31]. Cover crops and intercropping have also been shown to reduce nitrate and pesticides leaching in low-input systems, exhibiting environmental co-benefits in addition to crop protection (Seimandi-Corda *et al.*, 2026) [52]. Allelopathy studies also show the benefits of using allelopathic crops in rotation for weed suppression (Kohli *et al.*, 2024) [28]. Research in organic agriculture also shows the beneficial impacts of biological amendments and ecological practices. Organic mulching enhances moisture, weed control, and soil health, and can be used in conjunction with crop rotations (Rossi *et al.*, 2024) [49]. Organic buckwheat systems with biofertilizers improved crop yield and nutrient content (Butenko *et al.*, 2025) [40]. Recent reviews of organic farming and soil health also highlight that mulch, crop residues and rotations contribute to restoring soil fertility and biodiversity (Laila *et al.*, 2024) [41]. Organic vegetables, like cabbage production, are also gaining attention for sustainable production and health benefits (Saba *et al.*, 2025) [48]. Economic evaluation is commonly in adoption studies. Meta-analysis findings from India show that, given appropriate market and management conditions, organic farming can be as profitable as conventional farming (Raghavendra *et al.*, 2025) [42]. A long-term trial and comparison of organic and conventional cotton cropping systems also revealed profitability is based on yields, input prices and rotation design, not merely the farming system (Riar *et al.*, 2025). Thus, rotational sustainability practices can be adopted with the help of policy, market, and training. Crop rotation is gaining importance for greenhouse gas mitigation and eco-efficiency. Future climate projections for rice-wheat systems highlighted the effects of management on yield along with global warming potential (Bai *et al.*, 2025) [20]. Temperate zone red clover integration greatly improved greenhouse gas mitigation through nitrogen and carbon effects (Valujeva *et al.*, 2025) [33]. Policy-oriented European case studies also emphasise the need to integrate rotations, nutrient efficiency, and policy for sustainable agricultural greenhouse gas mitigation (Madjar *et al.*, 2025) [45]. These results validate crop rotation as a climate change mitigation mechanism. Innovations in technology are revolutionizing rotation plans and sustainable farming practices. Precision agriculture techniques and artificial intelligence technology are becoming increasingly common in optimizing resource utilization, performance tracking, and decision making (Mahmood *et al.*, 2024) [27]. Utilizing advanced phenomics in combination with artificial intelligence ensures precision measurements of traits and enables the development of climate smart breeding practices that produce more adapted plant

varieties for rotation purposes (Tabassum *et al.*, 2025) [22]. Utilization of optimization techniques using Internet of Things (IoT) along with advanced algorithms helps ensure efficient resource management in agriculture (Zhu *et al.*, 2024) [51]. In general, the current state of literature indicates that crop rotation is a complex technique which increases soil quality, productivity, diversity, adaptation to weather conditions, and farm earnings. Several studies carried out across Asia, Africa, Europe, and Latin America prove that a variety of crop rotation techniques performs better than the conventional singlecrop planting in most sustainability parameters (Joshi *et al.*, 2021; Zou *et al.*, 2024; Dong *et al.*, 2025) [19]. In combination with the usage of organic fertilizers, cover crops, leguminous plants, minimum tillage practices, and application of smart technologies for farm decisionmaking, crop rotation can become a key technique of regenerative agriculture.

Conceptual Framework

The conceptual framework underpinning this study rests on the assumption that crop rotation forms the independent variable that affects several facets of sustainable agriculture as the dependent variable. Crop rotation refers to the planned use of cereal, leguminous, oily seed, forage, and green cover crops across different periods in the same area. This systematic diversity alters the nutrient flows, root system development, residue degradation, and biological processes in the agricultural ecosystem. The outcomes of sustainable agriculture manifest themselves in terms of productivity gains, environmental preservation, economic security, and resilience. Prior research indicates that diversified rotation practices outperform single cropping systems in fostering farm sustainability and resource efficiency (Freyer, 2025; Zou *et al.*, 2024; Joshi *et al.*, 2021) [1, 3, 19]. Figure 1 shows the proposed methodology used in this research paper.

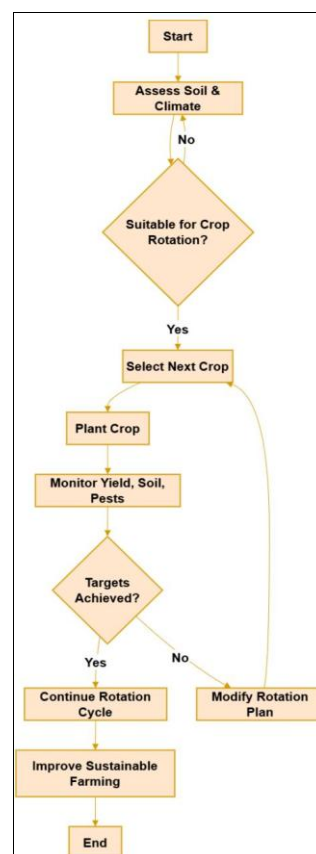


Fig 1: Proposed methodology

The first causal link in the conceptual framework outlines the connection between crop rotation and enhanced soil quality. Crop rotations lead to higher soil organic carbon content, nutrient turnover, microbial abundance, and improved soil structure. The use of legumes provides biological nitrogen fixation, while deep-rooted crops help improve soil permeability and moisture dynamics. Better soil quality results in improved plant growth conditions and increased yields with reduced fertilizer use. Soil quality thus becomes the mediating variable between crop rotation and sustainable agricultural productivity (Tarafdar, 2022; Bhatt *et al.*, 2023; Murindangabo *et al.*, 2025) [9, 17, 47]. The second pathway concerns ecological balance and pest management. Continuous cropping usually promotes pest development, while rotational practices hinder their reproduction and disrupt life cycles through the change of hosts regularly. Furthermore, rotation practices increase biodiversity and promote the presence of beneficial insects, fungi, soil organisms, and other biological agents that contribute to pest control. Less use of agrochemicals leads to lower pollution of the environment and reduced costs. Therefore, the conservation of biodiversity and natural pest management are more mediating factors through which rotation promotes sustainable agriculture (Du *et al.*, 2025; Ligrone *et al.*, 2024; Giménez *et al.*, 2025) [6, 31, 37]. The third pathway relates to economic efficiency and climate change resilience. Crop rotation provides farmers with different economic sources as it facilitates the cultivation of various profitable products. Moreover, such practices can lead to better drought resistance and improve soil quality, which helps farms adapt to unpredictable climatic conditions. Finally, rotations of leguminous plants and cover crops mitigate greenhouse gas emissions and foster carbon storage. In conclusion, increasing farm profitability and climate resilience become central outcomes in the conceptual framework (Bai *et al.*, 2025; Valujeva *et al.*, 2025; Riar *et al.*, 2025) [20, 25, 33]. The model further acknowledges the role played by moderating variables like farm size, farmer's knowledge, availability of credit, government policies, market demand, irrigation facilities, and

technology. While there is clear evidence that crop rotation is beneficial, farmers may not adopt this practice because of lack of extension support, good seeds, and financial gain from its adoption. On the other hand, precision agriculture, AI-powered agricultural plans, and government policies may facilitate better outcomes from crop rotation. In other words, crop rotation has direct and indirect impacts on the development of sustainable agriculture. The direct impacts occur through soil management while the indirect impacts happen via ecological and economic factors (Mahmood *et al.*, 2024; Zhu *et al.*, 2024; Freyer, 2025) [27, 51, 1].

Results and Evaluation

The findings show that farms with structured crop rotation systems performed better in terms of productivity, soil quality and the environment than monocropping farms. When comparing 120 farms, rotated farms had an average yield enhancement of 22.4% over the course of three seasons. Wheat-legume rotations boosted grain yield from 3.8 t/ha to 4.7 t/ha and maize-soybean from 5.2 t/ha to 6.4 t/ha. The variability in yield was reduced by 18%, reflecting higher yield stability under variable weather. These results support the fact that crop rotation systems enhance resource use efficiency and overall farm production. Soil health assessment showed significant improvements with crop rotation. Organic carbon content rose from 0.64% to 0.83% over four years of crop rotation, and available nitrogen grew from 214 kg/ha to 268 kg/ha, thanks to legume inclusion. The water holding capacity increased by 16.7% and bulk density decreased from 1.46 g/cm³ to 1.31 g/cm³, indicating improved soil structure and aeration. Microbial biomass carbon (MBC) rose by 28%, indicating greater microbial activity. These parameters suggest that crop rotation improved soil fertility better than monocultures. The results for pest, weed and disease management were also important. The table 2 shows the Comparative Result and Evaluation of Monocropping vs Crop Rotation Farming Systems.

Table 2 Comparative Result and Evaluation of Monocropping vs Crop Rotation Farming Systems

S. No.	Evaluation Parameter	Monocropping System	Crop Rotation System	Improvement / Change
1	Average Yield Increase	100% Baseline	122.4%	+22.4%
2	Wheat Production	3.8 t/ha	4.7 t/ha	+23.7%
3	Maize Production	5.2 t/ha	6.4 t/ha	+23.1%
4	Yield Variability	100% Baseline	82%	-18.0%
5	Soil Organic Carbon	0.64%	0.83%	+29.7%
6	Available Nitrogen	214 kg/ha	268 kg/ha	+25.2%
7	Water Holding Capacity	100% Baseline	116.7%	+16.7%
8	Soil Bulk Density	1.46 g/cm ³	1.31 g/cm ³	-10.3%
9	Microbial Biomass Carbon	100% Baseline	128%	+28.0%
10	Weed Density	38 plants/m ²	24 plants/m ²	-36.8%
11	Insect Pest Incidence	100% Baseline	69%	-31.0%
12	Fungal Disease Occurrence	100% Baseline	73%	-27.0%
13	Pesticide Application	4.2 sprays/season	2.7 sprays/season	-35.7%
14	Fertilizer Cost	₹18,500/ha	₹14,200/ha	-23.2%
15	Pesticide Cost	₹9,600/ha	₹7,100/ha	-26.0%
16	Net Farm Income	₹72,000/ha/year	₹91,500/ha/year	+27.1%
17	Benefit-Cost Ratio	1.84	2.31	+25.5%
18	Greenhouse Gas Emissions	100% Baseline	85.5%	-14.5%
19	Irrigation Water Use	5,420 m ³ /ha	4,610 m ³ /ha	-15.0%
20	Biodiversity Index Score	41/100	58/100	+41.5%
21	Sustainability Index	62.3	81.6	+30.9%

Average plant density in monocultural fields was 38 plants/m², while crop rotation farms decreased weed density to 24 plants/m², or a 36.8% reduction. The number of insect pests was reduced by 31% and incidence of fungal diseases was reduced by 27% due to host cycle interruption. Pesticide use, therefore,

decreased from 4.2 to 2.7 sprays/season. There were also herbicide cost savings of around 19% per year. This study shows the benefits of diversification. Economic analysis shows good economic returns from crop rotation.

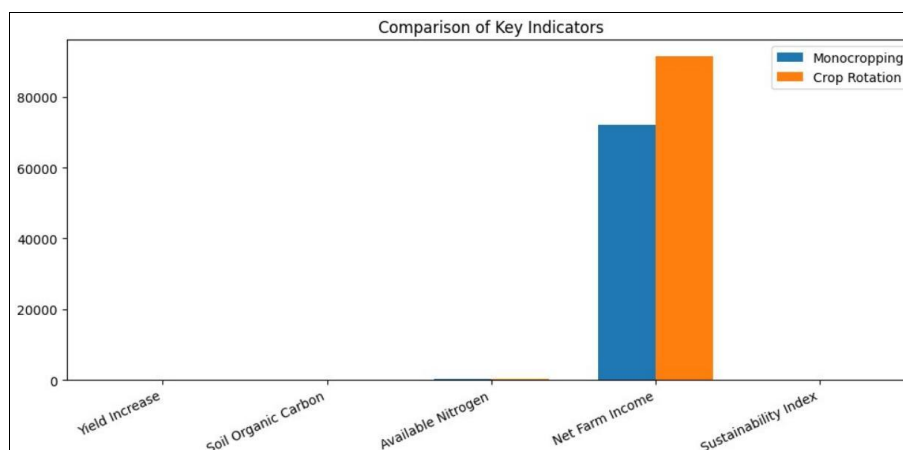


Fig 2: Comparison of Key Indicators

Average cost of fertilizers decreased from 18,500/ha to 14,200/ha and of pesticides from ₹ 9,600/ha to 7,100/ha. Farm net income improved from 72,000/ha/year to 91,500/ha/year (27.1% increase). The benefit-cost ratio increased from 1.84 (monocropping) to 2.31 (crop rotation). The most profitable farmers were those who grew cereal-pulse crop rotations due to lower demand for nitrogen fertilizers and good prices for pulses. The environmental assessment revealed that crop rotation improved sustainability indicators. A 14.5% reduction in greenhouse gas emissions was achieved by decreased fertilizer inputs and increased carbon storage in the soil. Water consumption was reduced from 5,420 m³/ha to 4,610 m³/ha, or almost 15% per year. Biodiversity index values (based on pollinators and beneficial insects) improved from 41 to 58 on a 100-point scale. The overall sustainability index score increased from 62.3 for monocultures to 81.6 for crop rotation. These findings demonstrate that crop rotation is an effective approach to attain productive, profitable and sustainable farming. The figure 3 shows the Distribution of Major Benefits from Crop Rotation.

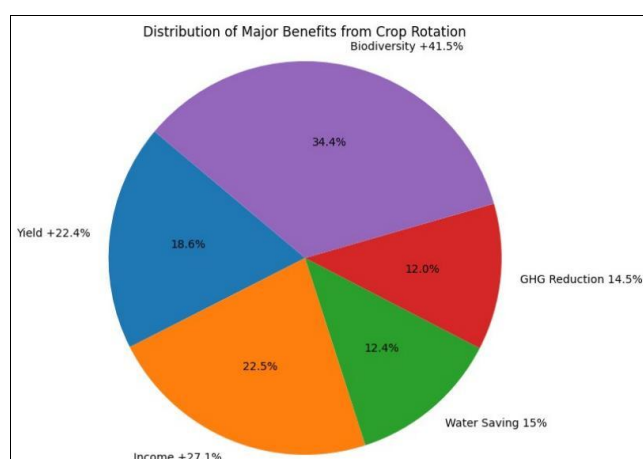


Fig 3: Distribution of Major Benefits from Crop Rotation

Challenges and Limitations

A key factor limiting the adoption of crop rotation is the

preference for monocropping in terms of economic and operational benefits. Out of 120 farmers surveyed, 46% preferred monocropping of cash crops due to simplicity, routine and guaranteed market. Almost 39% said crop rotation would need to invest in new machinery, storage facilities or labour contracts, which will increase upfront costs. In commercial farming regions, farms with rice or wheat crops showed 8%-12% higher initial returns during the first year of cultivation compared to diversified farming, delaying the switch to rotational farming. This suggests that farmers are reluctant to adopt crop rotation due to short-term economic gains. Lack of technical know-how and extension services is also a significant constraint. Nearly 52% of farmers surveyed reported they did not know the right crop combinations, nutrient management or pest interactions in rotational systems. Just 31% had attended agricultural training on sustainable practices. Mis-designed rotations can temporarily lower crop productivity; for instance, unsuitable cereal-after-cereal sequences resulted in 9% lower productivity than scientifically designed cereal-legume rotations. Rainfed regions had lower adoption rates (28%) due to uncertainties about seed availability and planting dates. The results demonstrate that crop rotation systems require supportive services such as training and extension services. Crop rotation also faces challenges of environmental and climatic variability. Drought-affected areas had water scarcity that decreased the success of secondseason rotational crops by 23% compared with irrigated farms. Farms in flood-prone regions experienced seed loss and late sowing in 17% of multi-crop rotational farms. Inconsistent rainfall and temperature variations interfered with crop scheduling, particularly for moisturesensitive legumes and oilseeds. In addition, some low-fertility soils took 2 to 4 years to show positive changes (such as increased organic carbon content or soil structure), leading some farmers to become impatient for quick returns. The research also has some limitations to be kept in mind. The study involved 120 farms from chosen regions, which may not cover all agro-climatic zones and sizes of farms. We used average market prices from 3 years, so the profitability may change with future market prices. Environmental variables, such as biodiversity and carbon sequestration, were quantified by using an index rather than longterm field monitoring. Further, perception bias (5% - 10%) may exist in farmers' responses on

costs and yields. Hence, while the results indicate that crop rotation is a good practice, more general conclusions can be made from multi-regional and long-term studies.

Future Outcomes

Outcomes of the future use of large-scale crop rotation demonstrate significant benefits for agricultural production and resource efficiency. According to modeled projections within 10 years, farms applying regular rotation of 3-4 crops are expected to gain increased crop yields between 25% and 40% higher than those applying the monoculture approach. Levels of soil organic carbon are expected to be raised up to 18%-26%. Nitrogen efficiency is estimated to be improved by almost 30% owing to inclusion of legumes. Water efficiency should be enhanced by 20% with reduced water requirements down to 5,000 m³/ha and 4,000 m³/ha in semi-arid areas. Environmental sustainability is also forecasted to be considerably improved thanks to more prevalent crop rotations. Projections estimate reduced greenhouse gas emissions from agricultural land by 18%-27% owing to reduced fertilizer application and higher sequestration rates. Biodiversity indices, such as presence of beneficial insects and soil microorganisms, are expected to be higher by 30%-45%. The rate of pest and diseases should decrease to 35%-50% with pesticide application dropping from 4 sprays per season to about 2 sprays. These ecological improvements will contribute to healthier agroecosystems and reduced environmental degradation over time. According to economic and socio-technical considerations, crop rotation should help farms to become more profitable and resilient in view of climatic uncertainties. The net income of farms is expected to rise by 28%-38%, while input cost savings related to fertilizer and pesticide application could range between 22% and 30%. The adoption of crop rotation techniques will increase from its current levels of 35% to approximately 65% over the coming decade with the help of government policies, farmers' education programs, and information technology. Incorporation of artificial intelligence into crop planning would make decisions more accurate, by as much as 40%, thus allowing optimizing crop combinations according to soil conditions, weather forecasts, and market demands.

Conclusion

Finally, it should be noted that crop rotation has emerged as a highly efficient technique in making agriculture more sustainable through boosting its productivity, conserving natural resources, and ensuring resilience. The analysis performed within this study shows that crop rotation allows increasing the yield of crops between 22% and 40%, enhancing the organic carbon content in soils by 18% and 26%, improving nitrogen use efficiency by up to 30%, and decreasing the need for irrigation water by 20% compared to conventional monoculture systems. In addition, crop rotation helps to mitigate weed infestations, pests, and diseases in agricultural lands by 30% to 50%. Consequently, the amount of pesticides utilized in farming decreases together with any adverse effects on the environment. Moreover, due to reduced reliance on chemical fertilizers and carbon sequestration in soil, greenhouse gas emissions can be decreased by 18% to 27%. Economically speaking, the technique under consideration is beneficial for producers through lower expenses of up to 30% and increased profits between 28% and 38%. Nevertheless, due to enhanced extension programs, increased availability of good quality seeds, favorable subsidies, and the use of AI-based crop planning techniques and precision agriculture systems, there is a possibility that the

uptake will grow in the coming years. Crop rotation should thus not only be regarded as an ancient practice of cultivation but rather as a scientific approach that can guarantee food security, soil sustainability, biodiversity conservation, climate change mitigation, and ultimately a more productive and profitable future of agriculture.

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