A REVIEW: ADOPTION OF MODERN TECHNOLOGY FOR SUSTAINABLE AGRICULTURE IN INDIA

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ABSTRACT

The global population is expanding at an unprecedented pace, creating tremendous pressure on agricultural systems to produce enough food to satisfy the increasing demand. At the same time, vital natural resources such as fertile soil, freshwater, and forests are being exploited extensively, often in unsustainable ways. This has raised significant concerns regarding the ability of future generations to access sufficient nutritious food, clean air, and a healthy ecosystem. Consequently, ensuring long-term food security while maintaining environmental sustainability has become one of the most critical global challenges. Although several factors contribute to this issue, one of the primary concerns is the slow adoption and inadequate implementation of advanced and sustainable agricultural technologies and practices. A wide range of innovative approaches has the potential to reshape modern agriculture and improve its resilience against environmental and economic challenges. These include climate-smart agriculture, precision farming, sustainable intensification, regenerative and biodynamic farming, organic agriculture, integrated nutrient and pest management and artificial intelligence, and big data-driven agricultural management. When effectively implemented, these approaches can significantly enhance agricultural productivity while minimizing adverse environmental impacts and promoting efficient resource utilization. Despite these advantages, the large-scale adoption of such practices remains limited due to several constraints, including insufficient awareness among farmers, inadequate technical expertise, financial limitations, restricted access to modern technologies, and weak institutional and policy support. As a result, the agricultural sector continues to face numerous challenges that restrict its productivity, hinder sustainable development, and reduce its contribution to national economic growth. Addressing these challenges requires the effective integration of traditional agricultural knowledge with emerging scientific innovations and digital technologies such a balanced approach can improve farming efficiency, optimize resource use, and support the development of more sustainable and productive food systems. Therefore, the present study aims to provide evidence-based and data-driven insights that can assist policymakers, researchers, and farmers in making informed decisions, improving agricultural productivity, encouraging sustainable development, ensuring the production of safe and high-quality food, and reinforcing long-term food security for both present and future generations.

Keywords: *Sustainable Agriculture, Modern Approaches, Climate Smart Agriculture, New Innovation technologies, Integrated Farming.*

INTRODUCTION

Due to the increasing demand for food, the global agriculture sector is facing dual challenges to increase productivity while tackling environmental issues (1). In response to these challenges, many regions worldwide are exploring approaches to transition toward more sustainable agricultural systems, leveraging digital technologies to enhance productivity while promoting environmental sustainability (2).

Alternative agricultural models are being adopted which are characterised by technological innovation, diversification, and sustainable practices are regarded as essential for overcoming regional challenges (3).

Innovative technologies play a major role in modernizing agriculture by innovating large amounts of valuable data through tools such as remote sensing, the Internet of things and valuable data. Going beyond traditional precision agriculture , these technologies can support sustainable agriculture through increased productivity, reduced environmental footprint, and improved resilience to climate challenges (4).

Sustainable agricultural practices help produce food and other agricultural products without causing harm to the environment. Their aim is to ensure that food remains available and accessible to people without affecting the ability of future generations to meet their own needs(5).Sustainable agriculture is an integrated approach to crop and livestock production that seeks to meet the food and fiber needs of people while protecting the environment, maintaining farm profitability, and improving the quality of life for farmers and society (6). It can be understood as a farming system that fulfills current agricultural and food requirements while preserving the capacity of present and future generations. This concept is based on the careful use and management of natural resources and the benefits provided by ecosystems. Discussions on agricultural sustainability encompass diverse perspectives, primarily represented by ecocentric and technocentric approaches (7).

The ecocentric perspective emphasizes harmony with nature through practices such as organic and biodynamic farming, while encouraging changes in resource use, allocation, and consumption patterns. In contrast, the technocentric perspective highlights the role of technological innovation, strategic planning, and lifestyle adjustments in achieving sustainable development (8).A holistic and interdisciplinary understanding of sustainable development incorporates elements from both perspectives. Within the technocentric framework, sustainability can be attained through a range of strategies, including improvements in industrial agricultural systems and the application of biotechnological innovations to address growing food demands (9).

Recent studies highlight that most discussions focus on environmental sustainability and productivity, while socio-economic and governance aspects receive less attention, even though they play a vital role in the successful adoption of agricultural innovations. The sustainability of food systems is often affected by problems such as ineffective governance, market barriers, and policies that do not align with one another (10).

According to (11), external factors affecting the spread of agricultural technologies have received less attention than other aspects of technology adoption. These factors include social networks, peer influence, government assistance, information availability, and regulatory and societal support. Additionally, concerns regarding data ownership and data sharing have become increasingly significant as agricultural technologies generate large amounts of data (12). Nevertheless, research on these issues remains limited, especially in understanding farmers' perceptions and experiences (13).

Sustainable agriculture is strongly associated with food security, as it contributes to food availability, equitable access, nutritional adequacy, food safety, and long-term economic sustainability (14).To address the long-term challenge of food security, modern sustainable farming methods and practices should be widely adopted and implemented at all levels of agricultural production(14)

1.TRADITIONAL AND MODERN AGRICULTURAL PRACTICES

India contains several long-established agricultural landscapes that have survived for centuries despite significant climate fluctuations and changing social conditions. Their long-term sustainability is largely attributed to strong resilience, which results from the integrated use of natural resources, the recycling of nutrients and materials, and the provision of multiple ecosystem and community benefits. However, these traditional systems often do not produce enough yield to satisfy current food requirements. Conversely, modern farming systems achieve much higher productivity and operational efficiency, but their tightly optimized design makes them more sensitive and less adaptable to shifts in climate conditions and market fluctuations (15).

Indian agriculture is highly labour-intensive and largely based on subsistence farming. Around 60% of the population relies on agriculture for their livelihood, and a significant portion of farmland depends on rainfall rather than irrigation.Although traditional farming is still practiced in several parts of the world, the process of modernization has significantly transformed agriculture. Conventional agriculture typically depends on age-old knowledge, basic tools, and organic inputs, while modern agriculture makes use of advanced technologies, improved equipment, and mechanized systems. With the growing influence of globalization and technological progress, many traditional practices and local farming knowledge are gradually becoming less relevant. As a result, the global food system has increasingly shifted from being supported by millions of small farmers to being controlled by a limited number of large agribusiness corporations. Modern agricultural systems emphasize high production, capital investment, intensive input use, and uniform crop yields. In contrast, traditional farming systems prioritize local adaptation, biodiversity, the preservation of genetic diversity, and cultural values associated with a wide variety of crops. This transition from traditional to modern agriculture can significantly affect both cultivated and wild plant diversity. To ensure long-term food security, agriculture must remain resilient in the face of global environmental challenges. Such resilience depends heavily on both biological and cultural diversity, as diversity provides alternatives if certain crops or practices fail. If modernization is balanced with increased conservation efforts, cultural diversity can play an important role in maintaining and protecting biodiversity (16).

1.1. Traditional Farming:

Traditional farming is an agricultural system that has been practiced for generations using indigenous knowledge, simple tools, family labour, and locally available resources. It depends largely on natural processes, organic manures, and inherited farming techniques rather than advanced machinery and modern technology. This form of agriculture is closely linked to the cultural traditions and lifestyles of rural communities.Prominent traditional agricultural practices include the following:

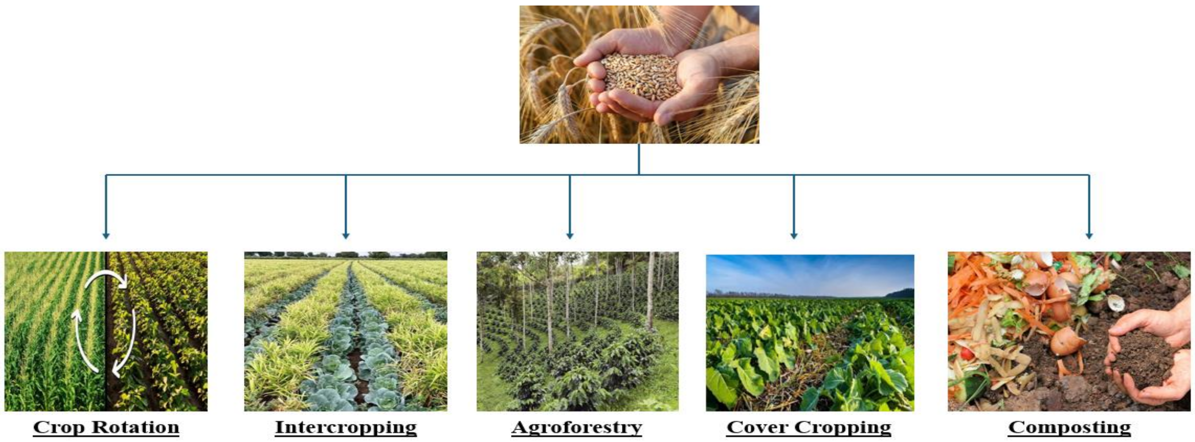

Fig 1: Types of Traditional farming methods

a. **Agroforestry:** Agroforestry is a traditional land-management system that originated alongside the advent of agriculture and animal husbandry (17), involves the cultivation of trees alongside agricultural crops. It has a potential for mitigation of the effects of climate change, adaptation, food security, and crop productivity (18)In addition, this practice contributes to improved soil quality, enhanced water retention, increased carbon sequestration, greater agrobiodiversity, and ultimately higher farmer incomes (19) The significance of agroforestry in drought-prone regions lies in the ability of deep-rooted trees to exploit a larger soil volume, thereby accessing water and nutrients that are unavailable to shallow-rooted crops.(20) Among the various agroforestry systems, the silvopastoral system is especially advantageous for livestock, as it involves the integration of trees with leguminous fodder grasses, thereby improving fodder availability and quality.(21)

b. **Crop rotation:** Crop rotation refers to the systematic cultivation of various crops on the same field in a specific order during different planting seasons to maintain soil health and productivity (22) This agricultural system offers several advantages, including enhanced soil health and fertility, improved carbon storage in the soil, higher crop productivity, efficient utilization of water resources, reduced soil erosion (23), and better recycling of nutrients. Incorporating leguminous crops into the rotation helps naturally enrich the soil with nitrogen, thereby decreasing the need for synthetic nitrogen fertilizers.

c. **Intercropping**: Intercropping refers to the system of growing different crops together in the same field during a particular growing season (24). Intercropping is regarded as a highly efficient farming practice because it makes better use of available resources such as land, water, and nutrients. This system enhances crop productivity while promoting biodiversity, improving ecosystem resilience, and increasing the overall stability of agricultural systems.(25)Growing more than one crop in a field enhances resilience to climatic fluctuations, as different crops respond differently to environmental stresses.(26) Intercropping pigeon pea with sorghum is an age-old farming practice that remains widely adopted.(27) Carbon sequestration (28), nitrogen fixation (29), reduction of requirement of external nitrogen fertilizers (30), increased availability of nitrogen and phosphorus (moisture-holding capacity, and cation exchange capacity. Furthermore, they promote carbon sequestration, mitigate greenhouse gas emissions, reduce soil 31), reduced soil erosion (32) are some of the additional benefits of this system.

d. **Cover Cropping**: Cover cropping is a traditional farming practice in which crops are grown primarily to protect the soil from erosion and prevent nutrient depletion(33). The use of cover crops instead of leaving land fallow helps reduce runoff and protects the soil from erosion (34). Cover crops, comprising both leguminous and non-leguminous species, are typically terminated or harvested before the establishment of the primary crop(35). In some production systems, they are maintained alongside the main crop to provide living mulch and support soil conservation (36). Cover crops play a significant role in improving soil biological and physical properties by increasing microbial biomass, supporting soil health, enhancing water retention, promoting nutrient cycling, suppressing weed growth, and contributing to carbon sequestration (37).Despite their agronomic advantages, cover crops can present several challenges, such as additional financial expenses, complications in soil cultivation practices, potential allelopathic interactions, increased labour demands, and enhanced disease susceptibility (38).

e. **Composting:**Composting is a traditional practice in which organic matter is decomposed by micro-organisms under control to produce compost, which can be used as an organic manure (39). The recycling of organic waste materials such as farmyard manure, household waste, sewage sludge, and crop residues into organic manure contributes significantly to soil fertility enhancement(40). Organic manures improve soil physical, chemical, and biological properties by increasing soil organic carbon, nitrogen content, microbial activity, erosion, aid in pest and disease management, and enhance the soil's tolerance to drought conditions (41).As a low-cost and sustainable rural enterprise, vermicompost production supports the livelihoods of rural women in India and plays a significant role in enhancing their economic and social empowerment (42)

1.2. Modern Farming:

Traditional farming practices are vulnerable to climate change, environmental stresses, and natural calamities, which can significantly reduce crop yields. Although advanced agricultural technologies have been developed to address these issues, their adoption in rural areas is often limited by a lack of farmer awareness and knowledge (43). Modern farming relies on mechanization, technological advancements, and increased resource inputs to improve agricultural efficiency and productivity. The use of farm machinery, improved crop varieties, fertilizers, and plant protection measures forms the basis of these systems, while several other localized farming practices are also followed across different regions of India (16).

TRADITIONAL FARMING	MODERN FARMING
Traditional farming is mainly based on labour-intensive	Modern farming is entirely based on capital intensive
Crop rotation, agroforestry, slash, and burn cultivation are some of the techniques which are practiced under traditional farming	Mono- cropping, and precision agriculture is some of the techniques practiced under modern farming
The traditional method of farming is environment friendly as natural manure is used as fertilizer	Modern method of farming is not environmental friendly as chemical fertilizers and pesticides are used
Traditional farming takes a longer duration for a crop to yield as a result the rate of production is low	Modern farming is a fast method of farming as it yields the crop at a faster duration, as a result, the rate of production is high
Under traditional farming, high inputs are required	Under modern farming low inputs are required

Table 1: Difference between traditional and modern farming.

2. MODERN APPROACHES FOR SUSTAINABLE AGRICULTURE:

To make farming sustainable, it is necessary to examine different agricultural approaches that consider the environment. These approaches aim to protect natural resources, improve farmers' incomes, and benefit society. Some methods, such as agroecology and sustainable intensification, evolved as farming techniques, while others, like carbon farming, became important through policy support (44).

These sustainable farming approaches can be used under different farming systems and environmental conditions. They consider the farm as a whole and are designed to improve its overall performance. Many of these approaches are supported by experts and organizations, and some, such as organic farming, also have certification labels in the market. Although some methods are broad, like agroecology and sustainable intensification, while others are more specific, such as permaculture and high nature value farming, they all help farmers make better decisions for the long-term management and sustainability of their farms (45).

2.1. Climate smart agriculture: In recent years, climate change has emerged as a critical concern for agriculture, posing serious risks to livelihoods and food security for millions of people around the world.

Current farming systems not only place pressure on natural resources but also play a major role in increasing greenhouse gas emissions. The large-scale loss of forests and degradation of productive land have reduced the planet's capacity to capture and store atmospheric carbon. Consequently, climate change poses a serious threat to more than a billion farming families worldwide, as the agricultural sector is particularly sensitive to changing climatic conditions (46). **Climate-Smart Agriculture (CSA)** offers an integrated approach to addressing the interconnected challenges of climate change, agricultural productivity, and food security. Rather than representing a new farming system, CSA serves as a framework for identifying agricultural practices and institutional strategies that are best suited to local climatic conditions. Its primary objective is to strengthen the resilience and adaptive capacity of agricultural systems while ensuring sustainable food production and long-term food security. Climate-Smart Agriculture aims to guide sustainable agricultural development through approaches that explicitly account for climate change (47).

CSA focuses on three key objectives: improving agricultural productivity and farmers' incomes, strengthening adaptation to climate change at multiple levels, and mitigating climate change by reducing emissions and increasing carbon sinks (48).

Fig 2: Goals of climate smart agriculture

Source- Sahu, G et al 2020

Long-term alterations in weather patterns lead to climate change, which poses a serious threat to agricultural productivity. Rising and falling temperature extremes, irregular rainfall, and increasing sea levels adversely affect crop production by degrading coastal freshwater resources and increasing the likelihood of flooding. The situation becomes more critical when extreme climatic events such as droughts, floods, and heat waves occur, as their frequency and intensity are expected to rise in the coming years. Developing countries, including India, are particularly susceptible to these impacts because their economies rely heavily on agriculture and they often have limited technological and financial capacity to effectively adapt to such climatic challenges (49).

Climate change, including the effects of global warming, influences every aspect of human life, with agriculture being one of the most vulnerable sectors. Recognizing the need to reduce climate-related risks in agriculture, the Indian Council of Agricultural Research (ICAR) launched the **National Innovations on Climate Resilient Agriculture (NICRA)** initiative. The project aims to strengthen the resilience of agricultural systems by promoting climate-resilient technologies, enhancing adaptive capacity, and minimizing the adverse impacts of climate variability and change. India is highly susceptible to the adverse effects of climate change because of persistent poverty, the dependence of nearly half of its population on agriculture for their livelihoods, the sector's strong reliance on natural resources, and limited capacity to cope with climatic shocks. Although the introduction of improved agricultural technologies during the mid-1960s—including high-yielding crop varieties, chemical fertilizers, and expanded irrigation—led to remarkable increases in food grain production and marked the beginning of the Green Revolution, concerns have emerged regarding the long-term sustainability of this production system. Ensuring sufficient food production for a rapidly growing population while maintaining environmental and resource sustainability has become a major challenge under changing climatic conditions (50).

Achieving sustainable agricultural development requires the adoption of effective strategies that promote Climate-Smart Agriculture (CSA). To support this objective, the Consultative Group on International Agricultural Research, through its Research Program on Climate Change, Agriculture and Food Security (CCAFS), has collaborated with national institutions and rural communities to establish Climate-Smart Villages (CSVs). These villages serve as demonstration models for implementing locally adapted climate-smart practices that enhance food security, strengthen farmers' capacity to adapt to climate change, and improve resilience against climatic stresses (51).

The **Climate-Smart Village (CSV)** approach was first introduced in the Indian states of Haryana and Bihar in 2011. Since then, smallholder farmers have adopted a variety of Climate-Smart Agriculture (CSA) practices to reduce the adverse impacts of climate change and climate variability while improving farm profitability. These practices include enhancing cropping systems through the use of improved crop varieties, crop diversification, crop rotation, and the integration of legumes. Farmers also employ integrated nutrient management techniques such as green manuring, compost application, and site-specific nutrient management. In addition, resource conservation measures like minimum or zero tillage, precision water management practices including raised-bed planting, laser land levelling, and crop residue mulching, as well as the integration of agroforestry systems, are being implemented to strengthen climate adaptation, improve resource-use efficiency, and enhance the resilience of agricultural production systems (52). The adoption of Climate-Smart Agriculture (CSA) practices and technologies has enabled smallholder farmers in the Indo-Gangetic Plains of India to improve agricultural productivity and generate higher incomes compared with conventional farming methods. These positive outcomes indicate that expanding the implementation of CSA interventions to other regions could enhance farmers' economic returns while increasing their resilience to climate variability and change. Under the **CGIAR's Climate Change, Agriculture and Food Security (CCAFS)** program, the application of climate-smart technologies across different parts of India has contributed to increased crop yields, improved farm profitability, greater efficiency in the use of agricultural inputs, and reduced greenhouse gas (GHG) emissions. However, the widespread transition to climate-smart farming will depend largely on the adoption of innovative agricultural technologies, supported by effective extension services and adequate access to institutional credit (53). Expanding financial support for climate-smart farming by integrating climate finance with conventional agricultural credit can play a crucial role in accelerating the adoption of sustainable farming practices. Improved access to targeted financial resources would encourage farmers to invest in climate-resilient technologies, thereby enhancing agricultural sustainability, strengthening rural livelihoods, and ensuring long-term food security. Such financial integration can significantly contribute to building a more resilient and economically viable agricultural sector capable of addressing the challenges posed by climate change.

2.2. Organic Farming: Organic farming is a sustainable agricultural system that focuses on conserving the environment, ensuring animal welfare, producing safe and high-quality food, promoting the efficient use of natural resources, and supporting social equity (54). Organic farming seeks to establish integrated, environmentally responsible, and economically viable production systems by utilizing renewable resources and effectively managing natural ecological and biological processes. This approach aims to ensure adequate food production while providing sustainable economic benefits to farmers (55). Organic farming requires lower financial investment than conventional farming systems. It also enhances the ability of farmers and rural communities to cope with the adverse impacts of climate change. Moreover, by promoting sustainable resource management and resilient agricultural practices, organic farming meets many of the key criteria for effective climate change adaptation strategies (56).

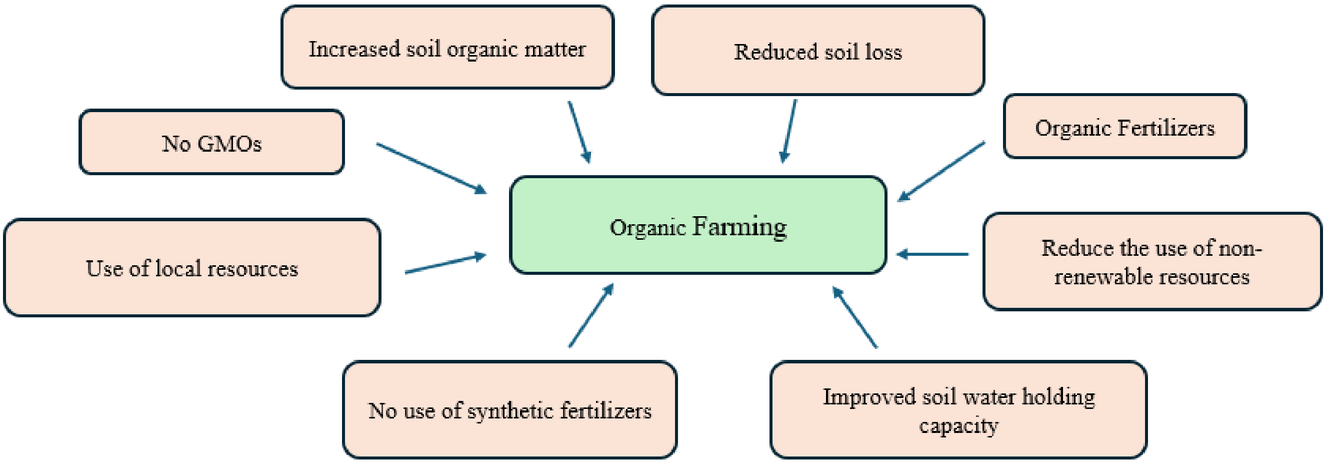

Fig 3: The main practices and effects of organic farming

Organic farming is among the fastest-expanding agricultural sectors worldwide and currently accounts for approximately 1% of the global agricultural land. It is a sustainable farming system that relies on naturally derived fertilizers, including compost, green manure, and bone meal, instead of synthetic inputs. Organic farming also emphasizes ecological management practices such as crop rotation, companion planting, and the efficient recycling of organic resources to maintain soil fertility, improve biodiversity, and support long-term agricultural sustainability (58).

Organic farming incorporates several sustainable agricultural practices that enhance environmental quality and resource-use efficiency. These include the adoption of integrated pest management (IPM) strategies to minimize pesticide use, crop rotation, and the cultivation of nitrogen-fixing cover crops to improve soil fertility and maintain soil health. The application of mulches further supports moisture conservation and reduces soil erosion. Conservation tillage practices, such as no-till or reduced tillage, help prevent soil compaction and preserve soil structure. Nutrient management is guided by regular soil testing, enabling the precise application of organic and, when necessary, synthetic fertilizers while encouraging greater reliance on organic nutrient sources. In addition, modern irrigation systems are designed to optimize water use efficiency, increase crop productivity, and reduce water losses, soil erosion, and salinity, thereby contributing to the long-term sustainability of agricultural production (59). Organic farming encourages the use of ground cover, cover crops, and mulches to protect the soil from erosion while reducing dependence on chemical pesticides and promoting biodiversity conservation. It has emerged as a rapidly expanding agricultural sector because of its potential health, environmental, and economic benefits. Growing consumer awareness of the possible health risks associated with chemically produced food has increased the demand for organic products, with many consumers willing to pay premium prices for them. In addition, increasing environmental awareness and a commitment to sustainable resource management have further encouraged the adoption and purchase of organically produced food, supporting both ecosystem conservation and sustainable agricultural development.

2.2.1. New innovation technologies for organic farming:Organic farming has become an essential tool when moving towards the future era to decrease the adverse effect of burning crops and global warming. Modern agricultural practices involve the use of chemical fertilizers and pesticides to meet the challenges of agriculture. Modern organic farming was developed as a response to the environmental harm caused by the use of chemical pesticides and synthetic fertilizers in modern agriculture, and it has numerous ecological benefits. A combination of organic fertilizer and new technologies is of utmost importance to reduce the limitations and challenges of organic fertilizer.

a. **Sludge**: Sludge is a semi-solid by-product generated from various industrial activities, water treatment facilities, wastewater treatment plants, and sanitation systems. It is rich in organic matter and essential plant nutrients, particularly nitrogen and phosphorus, making it a valuable resource for use as an organic fertilizer and soil amendment. When properly treated and managed, sludge can improve soil fertility and support sustainable agricultural production. Several studies have investigated the potential of wastewater treatment plant sludge as an organic fertilizer, demonstrating its effectiveness in enhancing soil quality and crop productivity.

Uses of sludge	**Importance**	**Reference**
Organic mineral fertilizer	The sustainable production of locally available resources and low-carbon impact nitrogen supply	(60)
Sewage sludge soil application	Some micronutrients and N were more efficiently supplied to maize plants by sewage sludge	(61)
Sewage sludge as organic fertilizer	Enhance the economic yield of wheat and improve productivity	(62)

Application of sludge on cropland	A sustainable management practice	(63)
Gamma irradiated sewage sludge as fertilizer in radish	No discernible differences were observed among the fertilizer sources. The levels of metallic micronutrients and heavy metals in the soil remained below the limits recommended by the U.S. Environmental Protection Agency(USEPA), and even at higher application rates, no appreciable changes were observed after two years.	(64)

Table 2: Uses of sludge and its importance

b. **Biochar with organic fertilizer:** Biochar is produced from a wide range of carbon-rich feedstocks, including animal manure, food residues, sewage sludge, industrial by-products, wood chips, agricultural residues, and forestry waste. The chemical and physical characteristics of biochar vary depending on the type of biomass used. Various thermochemical conversion techniques are employed for its production, such as torrefaction, pyrolysis (slow, fast, and intermediate), hydrothermal carbonization, gasification, and flash carbonization. Among these methods, pyrolysis is the most commonly adopted process for converting biomass into biochar(65). Organic fertilizers and biochar are widely applied in agriculture to improve soil quality and increase crop productivity(66).The application of anaerobically digested rice straw compost together with rice husk biochar-coated urea has been shown to enhance soil nutrient availability. Furthermore, integrating biochar with either organic or chemical fertilizers generally produces better crop yield and plant nutrient uptake than using fertilizers alone. The combination of biochar-coated chemical fertilizers and organic fertilizers also functions as an effective slow-release nutrient source, improving nutrient use efficiency. Additionally, coating chemical fertilizers with biochar helps reduce nutrient losses through leaching and runoff, thereby minimizing the risk of inorganic fertilizer contamination in nearby water bodies (67).

c. **Biofertilizer:** Biofertilizers are formulations containing one or more beneficial microorganisms that enhance the essential nutrient availability to plants with the help of various biological processes. These processes include the decomposition of organic matter in soil and compost, biological nitrogen fixation, phosphate solubilization, and the production of plant growth-promoting substances and cellulolytic enzymes. As natural and eco-friendly nutrient sources, biofertilizers consist of living microbial inoculants, including free-living nitrogen-fixing bacteria such as *Azotobacter* and *Rhodospirillum*, as well as algae and fungi, if provided individually or both together will help in improving the soil fertility and support plant growth. The use of bio-organic fertilizers has been reported to increase soil organic carbon content by approximately 6–13% and promote the proliferation of plant growth-promoting bacteria compared with the sole application of chemical fertilizers. Furthermore, bio-organic fertilizers represent an environmentally sustainable approach that can reduce the requirement for chemical nitrogen fertilizers by up to 30% and completely replace triple superphosphate (TSP) in rice cultivation. By enhancing nutrient availability through natural biological processes, biofertilizers help lower dependence on synthetic fertilizers, thereby reducing production costs and mitigating their adverse impacts on soil health and environmental quality (68).Vermicomposting is a biological process in which biodegradable organic wastes are transformed into nutrient-rich organic manure through the activity of earthworms. This method is characterized by rapid compost production, the absence of unpleasant odors, and the elimination of the need for regular turning of compost piles. Earthworms are typically cultured in a mixture of animal manure, agricultural residues, soil, and partially decomposed leaf litter. During the process, these organic materials are converted into vermicompost, a stable and nutrient-rich fertilizer suitable for improving soil fertility and supporting the growth of a wide variety of crops and plants.

d. **Organomineral fertilizers:** Organomineral fertilizers are produced by combining organic materials with mineral nutrient sources in different nitrogen (N), phosphorus (P), and potassium (K) ratios to meet the nutritional needs of specific crops. These fertilizers are available in granulated, pelleted, or powdered forms. Their application improves soil fertility by enhancing its physical and chemical properties, increasing nutrient availability, improving water-holding capacity, and promoting phosphate solubilization. Moreover, organomineral fertilizers positively influence plant growth and physiological performance by enhancing nutrient uptake, stimulating metabolic activities, increasing biomass production, and ultimately improving crop yield (69).

e. **Digital technology:** Digital technologies and smart farming tools play an important role in organic agriculture by enabling farmers to monitor crop performance and livestock health, optimize resource utilization, reduce environmental impacts, and improve farm profitability. These technologies support various farming operations, including tillage, irrigation, nutrient management, post-harvest handling, storage, and transportation of agricultural produce. The adoption of digital agriculture also has the potential to enhance food security and reduce poverty, particularly among smallholder farmers, by improving productivity and decision-making. However, advanced digital technologies are currently more accessible to large-scale farming enterprises, where they contribute significantly to sustainable agricultural practices. Expanding reliable and affordable digital services for smallholder farmers remains essential for strengthening the economic and environmental sustainability of organic farming in the future (70).

2.3. Integrated farming system: Integrated Farming Systems (IFS), which combine multiple agricultural enterprises within a single production system, have considerable potential to enhance productivity, increase farm profitability, promote environmental sustainability, and strengthen resilience. By integrating diverse farming components, IFS offers an effective approach to addressing complex challenges such as food security, resource conservation, and climate change adaptation. Ensuring food and livelihood security, protecting the environment, and conserving natural resources have emerged as major global priorities in recent decades. Developing countries, in particular, face significant challenges due to the combined impacts of globalization and climate change, which have increased the vulnerability of agricultural production and contributed to frequent crop failures. Globally, smallholder farming dominates the agricultural sector, with more than 410 million farms covering less than one hectare and over 475 million farms occupying less than two hectares. Together, these farms account for approximately 72% and 84% of all agricultural holdings worldwide, highlighting the crucial role of small-scale farmers in global food production (71). It represents an effective model of sustainable agriculture, offering a wide range of economic, social, and environmental benefits.

By integrating multiple farm enterprises, IFS provides a comprehensive and practical approach to overcoming the challenges faced by small and marginal farmers, while enhancing productivity, profitability, resource-use efficiency, and livelihood security (72).

It can be described as a biologically integrated production system in which natural resources are effectively incorporated into agricultural practices through carefully regulated ecological processes. This approach minimizes reliance on off-farm inputs while ensuring sustainable productivity and long-term farm profitability(73). Integrated Farming Systems (IFS) represent an environmentally sound, economically feasible, and farmer-oriented approach that integrates indigenous knowledge with contemporary agricultural technologies. The system emphasizes context-specific management practices to optimize resource utilization, improve resilience, and promote sustainable agricultural development (74). Further, this system is believed to enhance productivity by 2-3 times, provide additional jobs, conserve 40-60% of resources and guarantee 100% household nutritional security(75).

An Integrated Farming System (IFS) may comprise a diverse range of interconnected enterprises, including seasonal crop cultivation, horticulture (fruits, vegetables, and spices), agroforestry, mushroom production, sericulture, poultry, pigeon and duck farming, azolla cultivation, fodder production, small ruminant rearing (sheep and goats), dairy farming, apiculture, and aquaculture. These components are integrated to improve resource utilization, diversify farm outputs, and enhance overall farm sustainability(76).

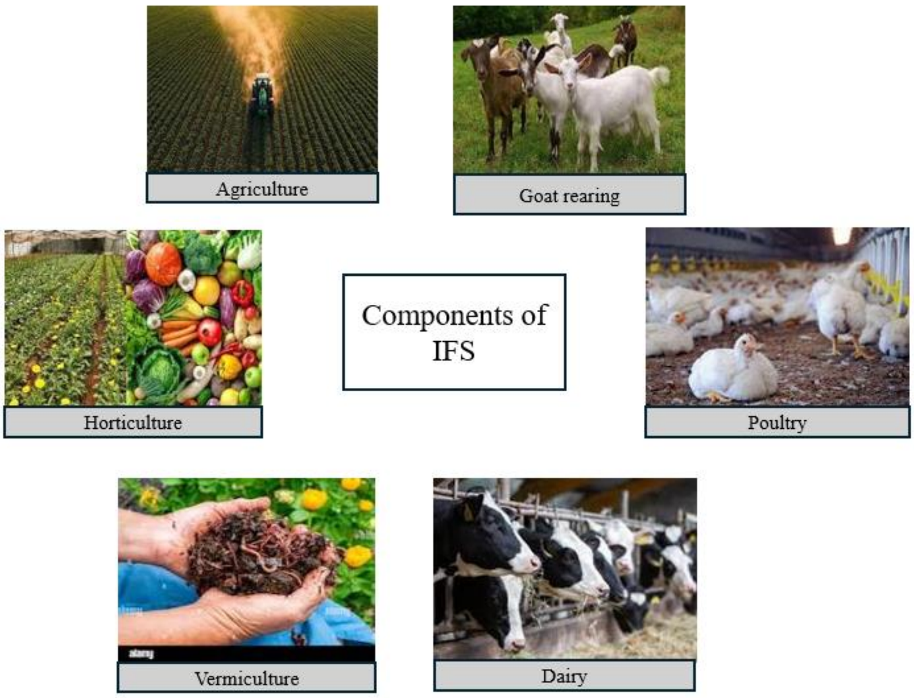

Fig 4: Various components under Integrated farming system (IFS)

2.3.1. Advantages of Integrated Crop–Livestock Farming System

a. Higher Productivity and Profitability: Integrated crop–livestock farming improves overall farm productivity by combining different crop and livestock enterprises that efficiently utilize available resources. Crop residues are used as livestock feed, while animal manure is recycled as organic fertilizer, reducing dependence on external inputs and lowering production costs.

The diversification of enterprises generates multiple sources of income, increases farm self-sufficiency, and enhances profitability, particularly for small and marginal farmers (77).

b. Improved Soil Health: The recycling of livestock manure and other organic farm wastes enriches the soil with essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K), thereby improving soil fertility and productivity. Diverse cropping patterns and continuous addition of organic matter enhance soil structure, microbial activity, and water-holding capacity. Grazing by livestock also helps suppress weeds, reducing the use of herbicides and pesticides, which further contributes to maintaining healthy and fertile soils (78).

c. Biodiversity Conservation: Integrated farming promotes biodiversity by incorporating diverse enterprises such as crops, livestock, agroforestry, fodder production, and cover crops within the same farming system. Reduced dependence on synthetic fertilizers and pesticides encourages beneficial insects, pollinators, and soil microorganisms. These practices help maintain ecological balance, create diverse habitats, preserve trophic interactions, and strengthen the resilience of agro ecosystems (79).

d. Reduced Greenhouse Gas Emissions: Integrated crop–livestock systems contribute to climate change mitigation by promoting the recycling of crop residues and livestock wastes, thereby reducing greenhouse gas emissions associated with waste disposal and chemical input production (80). Conservation practices such as no-till farming, moderate grazing, and efficient nutrient management increase soil organic carbon storage, which helps offset emissions of methane (CH_3) and nitrous oxide (N_2O). The efficient utilization of farm resources also reduces the need for energy-intensive agricultural operations (81).

e. Balanced Food and Nutritional Security: The integration of crops, horticulture, dairy, poultry, fisheries, mushroom cultivation, and other allied enterprises ensures the production of a wide variety of nutritious foods throughout the year. Fruits, vegetables, milk, eggs, meat, and fish provide essential vitamins, minerals, proteins, and energy, improving the nutritional status of farm families (82). This diversified production system enhances household food security while reducing dependence on external food sources.

f. Natural Pest and Weed Management: Livestock play an important role in the biological control of weeds and pests. Poultry consume weed seeds, young weeds, insects, and other crop pests, while grazing animals suppress weed growth and disturb pest habitats, reducing their population. Such natural pest and weed management practices decrease the reliance on chemical pesticides and herbicides, lowering production costs and minimizing environmental pollution (83).

g. Employment Generation and Women's Participation: The integration of multiple farming enterprises creates year-round employment opportunities by increasing labour requirements for crop cultivation, livestock management, dairy farming, poultry, fisheries, and other activities. This continuous demand for labour helps reduce seasonal unemployment in rural areas (84). Women actively participate in enterprises such as dairy farming, poultry rearing, goat and sheep rearing, vegetable cultivation, and the sale of milk, eggs, and vegetables, thereby strengthening household income and promoting gender participation in agriculture.

h. Year-Round Income Generation: Integrated farming provides farmers with continuous income by combining enterprises that generate returns at different times of the year. While crops provide seasonal income, dairy, poultry, fisheries, mushroom cultivation, and other allied activities offer regular cash flow throughout the year. This diversified income pattern reduces financial risks, improves resilience to climate and market fluctuations, conserves farm resources, and enhances the economic stability of farming households (85).

2.4. <u>Precision farming:</u> Precision farming is an advanced agricultural approach that utilizes modern technologies to measure, monitor, and analyze the specific requirements of individual fields and crops. It enables farmers to make site-specific management decisions, improving resource-use efficiency, crop productivity, and overall farm sustainability (86).Precision farming is an advanced farming approach that focuses on site-specific management by integrating modern technologies to optimize agricultural inputs, increase productivity, and promote sustainable farming practices (87). The fundamental principle of precision agriculture is the recognition and management of spatial and temporal variability within agricultural fields. Since soil characteristics, moisture levels, nutrient availability, and crop growth conditions vary across different parts of the same field, applying inputs uniformly often results in inefficient resource use and environmental degradation. To address this variability, precision agriculture integrates advanced technologies such as the Global Positioning System (GPS), Geographic Information System (GIS), and remote sensing for accurate field monitoring and site-specific management. These technologies support informed decision-making, improve input-use efficiency, enhance crop productivity, and promote environmentally sustainable farming practices (88). Precision farming has the potential to enhance the sustainability and resilience of food production systems by improving resource-use efficiency, optimizing crop management, and reducing environmental impacts. Although its adoption is challenged by factors such as high initial investment costs and limited technical knowledge among farmers, continued technological advancements and capacity-building efforts can promote its wider implementation and long-term benefits(87). Precision agriculture emphasizes the identification and management of field variability to optimize crop yields, improve input-use efficiency, and support sustainable agricultural production (88). A key principle of precision agriculture is the use of accurate field-level information to support informed agronomic decision-making. Data collected through soil testing, crop monitoring, spatial mapping, and advanced sensing technologies provide a scientific basis for site-specific management practices. By applying inputs according to the actual needs of crops and different field conditions, precision agriculture minimizes resource wastage, improves input-use efficiency, and enhances crop productivity while promoting sustainable farming practices (89). Precision agriculture is based on the principle of continuous monitoring of field conditions to identify spatial and temporal variability throughout the crop-growing season. Advanced technologies such as the Global Positioning System (GPS), Geographic Information System (GIS), and remote sensing enable accurate field mapping, data collection, and variability analysis. The integration of these digital technologies supports timely, site-specific management decisions, improving the efficiency, productivity, and sustainability of modern agricultural systems (86). Overall, precision agriculture is an advanced farm management system that combines modern technologies with scientific knowledge of agriculture to support efficient resource management, improve productivity, and promote sustainable farming practices.

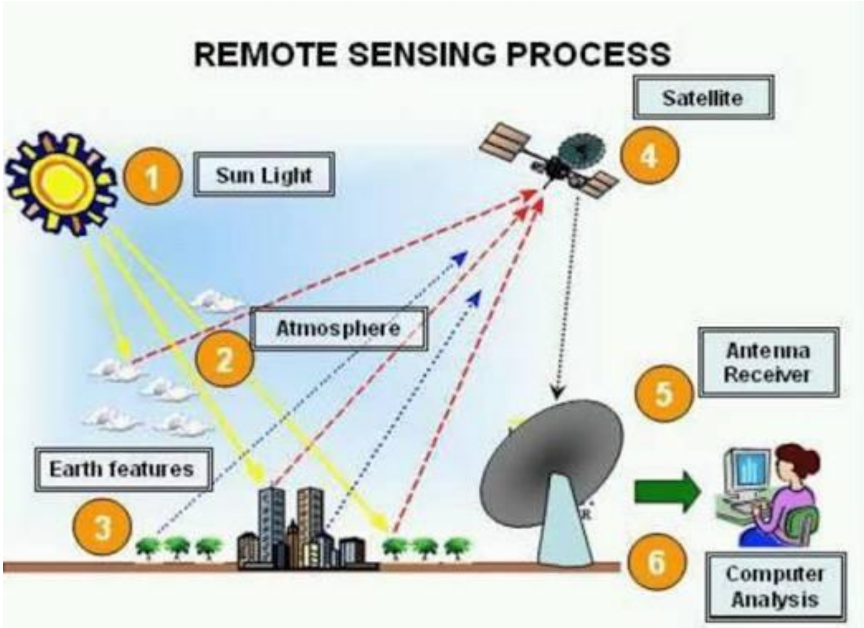

Fig 5: Satellite imagery and drone-based observations

Precision agriculture is based on the integration of advanced technologies that facilitate the accurate monitoring, analysis, and management of variability within agricultural fields. These technologies support site-specific decision-making, optimize the use of agricultural inputs, and improve crop productivity while promoting sustainable and resource-efficient farming practices (91).

The Global Positioning System (GPS) and Geographic Information System (GIS) are fundamental technologies in precision agriculture. GPS provides accurate real-time location information, enabling precise mapping of field boundaries, soil variability, crop conditions, and farm operations. It also guides agricultural machinery such as tractors, planters, sprayers, and harvesters, ensuring accurate field operations with minimal overlap or missed areas. GIS complements GPS by storing, analyzing, and visualizing spatial data related to soil properties, crop performance, and yield variability. Together, GPS and GIS support site-specific management, improve the precision of planting, fertilization, pesticide application, and harvesting, reduce input wastage and operational costs, and enhance overall farm productivity and resource-use efficiency.GPS enables site-specific farm management by supporting variable-rate application of agricultural inputs according to field conditions. It also facilitates yield monitoring by linking yield data to specific field locations, allowing farmers to evaluate field performance, identify productivity variations, and make informed management decisions for future cropping seasons.

A Geographic Information System (GIS) is a tool for analysis and decision-making that combines, stores, analyzes, and displays spatial data from GPS, remote sensing, and field sensors. GIS is used in precision farming to make precise computerized maps of things like soil qualities, crop health, nutrient levels, moisture levels, pest infestations, and changes in yield. These maps of space enable farmers and agronomists comprehend how different parts of a field are different from each other and make smart management choices that are specific to each site. GIS helps plan and evaluate precision farming treatments, which leads to better land use, better resource allocation, and better environmental management. GIS improves decision-making on crop management, irrigation scheduling, nutrient application, and long-term farm planning by combining different data layers. Together, these tools assist in field mapping and planning site-specific management practices (92).

Fig 6: Various aspect of GIS

2.4.1. Remote sensing is a key technology in precision agriculture that enables continuous, non-destructive monitoring of crop growth and field conditions over large areas. Data collected through satellites, aerial platforms, and drones equipped with multispectral, hyperspectral, or thermal sensors help assess crop vigor, nutrient deficiency, moisture status, and the incidence of pests and diseases. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) facilitate the early detection of crop stress, allowing timely and site-specific management interventions. Remote sensing also supports soil moisture assessment, irrigation scheduling, yield estimation, crop mapping, and land-use planning. In addition, high-resolution imagery helps identify pest- and weed-infested areas, enabling targeted pesticide application and reducing chemical use. Overall, remote sensing improves resource-use efficiency, minimizes yield losses, and enhances the sustainability of precision farming (93).

2.4.2. Sensor-based technologies and the Internet of Things (IoT) play a vital role in precision agriculture by enabling real-time monitoring, automation, and data-driven decision-making. A network of interconnected sensors continuously collects and transmits information on soil moisture, temperature, nutrient levels, pH, salinity, humidity, and other environmental parameters. This real-time data helps farmers apply irrigation, fertilizers, and other agricultural inputs precisely according to crop requirements, thereby improving resource-use efficiency and reducing wastage. In addition, IoT-based weather sensors monitor local conditions such as rainfall, air temperature, humidity, wind speed, and solar radiation, allowing farmers to make timely and informed management decisions that enhance crop productivity and sustainability (94).

2.4.3. Variable Rate Technology (VRT) is an important component of precision agriculture that enables the site-specific application of inputs such as seeds, fertilizers, irrigation water, and agrochemicals according to the varying needs of different field locations. Using spatial data and information on crop requirements, VRT regulates the amount of inputs applied in each area, ensuring optimal resource utilization. This technology improves input-use efficiency, reduces wastage and production costs, minimizes environmental pollution caused by excessive input application, and enhances crop productivity and sustainability (88). Variable Rate Technology (VRT) is a key component of precision agriculture that enables the application of agricultural inputs according to the spatial and temporal variability within a field. It uses information from soil tests, yield maps, remote sensing, GPS, GIS, and sensor-based technologies to apply fertilizers, irrigation water, seeds, and other inputs at variable rates based on site-specific requirements. This approach improves nutrient management by preventing the over- or under-application of fertilizers, thereby reducing nutrient losses through leaching, runoff, and volatilization. VRT also supports precision irrigation by supplying water according to soil moisture, crop growth stage, and local weather conditions, leading to improved water-use efficiency, lower energy consumption, enhanced crop productivity, and reduced environmental impact (95).

2.5. Integrated pest and disease management: Integrated Pest Management (IPM) is a comprehensive and environmentally sustainable approach to pest management that integrates cultural, biological, mechanical, and chemical control methods. Its primary objective is to keep pest populations below economically damaging levels while minimizing adverse effects on the environment, human health, and beneficial organisms (96). IPM emphasizes preventive practices, regular pest monitoring, and informed decision-making based on established economic threshold levels, rather than relying solely on routine or reactive pesticide applications. This approach ensures effective pest control while reducing unnecessary pesticide use and promoting sustainable agriculture(97). The fundamental principles of Integrated Pest Management include preventing pest outbreaks through cultural practices, regular monitoring of pest populations, and making control decisions based on economic threshold levels. It integrates biological, mechanical, physical, and chemical control methods to manage pests effectively while minimizing environmental impacts. Continuous evaluation of management practices helps improve the efficiency and sustainability of pest control(98). Sustainable pest management practices within the Integrated Pest Management framework play a crucial role in meeting the growing global food demand while conserving natural resources and reducing the impacts of climate change (99). IPM not only reduces crop losses caused by pests but also supports sustainable development by conserving natural resources, protecting human health, and improving environmental, social, and economic well-being.

2.5.1. Components of IPM*:* Integrated Pest Management (IPM) combines multiple pest control strategies, including preventive and cultural practices such as crop rotation, sanitation, intercropping, and resistant varieties, along with regular pest monitoring and decision-making based on economic thresholds. It also incorporates biological control through natural enemies and the judicious use of selective chemical pesticides only when necessary. By integrating these approaches, IPM effectively manages pests while minimizing risks to human health and the environment.

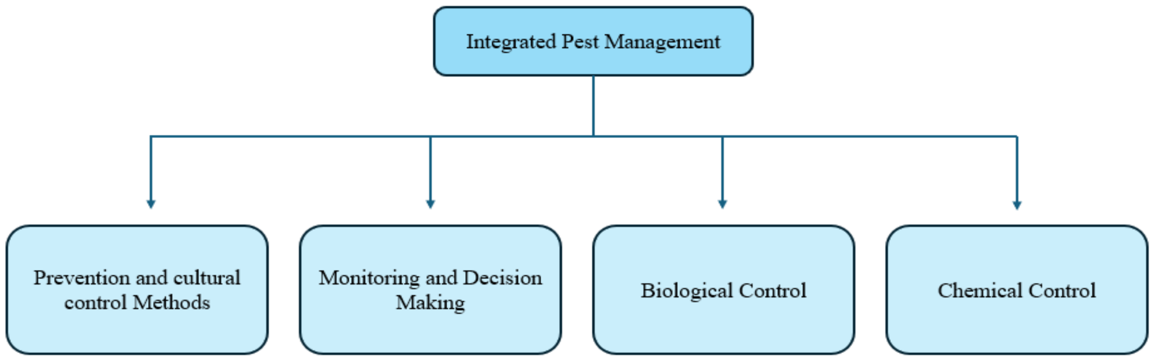

Fig 7: Key components of an Integrated Pest Management (IPM)

A. Prevention and Cultural Control Methods. Crop rotation is a key preventive practice in Integrated Pest Management that involves growing different crops in the same field in successive seasons to break pest life cycles, reduce pest populations, and improve overall crop health (101). The effectiveness of crop rotation in IPM depends on the proper selection and sequence of crops, the diversity of crops included, the duration of the rotation cycle, and the incorporation of cover crops or green manures to suppress pests and improve soil health (101). Intercropping is an important cultural practice in Integrated Pest Management (IPM) that involves growing two or more crop species simultaneously in the same field. It helps suppress pest populations by enhancing biodiversity, disrupting pest movement, and promoting natural enemies. The success of intercropping depends on the appropriate selection of companion crops, their spatial arrangement, and the timing of planting (102).

Sanitation practices are preventive cultural pest management measures that involve removing and destroying pest-infested plant parts, crop residues, and other potential sources of pest infestation from fields and nearby areas. These practices help reduce the buildup of pest populations, limit their survival and spread across growing seasons, and decrease the need for corrective pest control measures (103).

B. Monitoring and Decision Making. Scouting and sampling techniques are fundamental components of the monitoring and decision-making process in IPM programs (104). In addition to different sampling designs, a range of tools and techniques are used to monitor pest populations and assess their impact on crops. These include visual field inspections, sweep nets, sticky traps, pheromone traps, and advanced remote sensing technologies. Modern remote sensing methods, such as aerial imaging, satellite observations, and unmanned aerial vehicles (UAVs), enable large-scale monitoring of crop health and early detection of pest infestations.

The combined use of appropriate sampling strategies and multiple monitoring techniques supports informed, data-driven decisions on the timing and need for pest management interventions. More recently, artificial intelligence (AI) has emerged as a valuable tool in IPM, improving pest identification and assisting in decision-making processes (105)

C.Biological Control. Natural enemies such as parasitoids, predators, and pathogens are essential agents of biological control and constitute a core element of Integrated Pest Management (IPM) programs. Beneficial organisms regulate pest populations through diverse biological mechanisms such as direct predation, parasitism, and infection, often keeping pest densities below the economic threshold and minimizing crop losses (106). Predators represent a diverse group of natural enemies, encompassing arthropods such as ladybird beetles, lacewings, and spiders, as well as vertebrates including birds and rodents. Through continuous hunting and consumption of multiple prey individuals over their life cycle, they contribute significantly to the biological regulation of pest populations. The contribution of predators to biological pest control is governed by multiple ecological parameters, including feeding rate, functional and numerical responses, prey preference, and other biotic interactions. In contrast, parasitoids employ a distinct strategy in which eggs are laid on or within a host organism, allowing the developing larvae to utilize the host as a nutrient source and ultimately result in its death (107).

D.Chemical Control. Chemical control represents one of the most rapidly evolving components of IPM, with recent innovations focusing on selective pesticide application, resistance management, biopesticide development, natural bioactive compounds, and nanotechnology-based pest management approaches. Within Integrated Pest Management (IPM), chemical control is applied strategically through the careful and precise use of pesticides directed at specific pests or infested areas. This targeted approach minimizes unnecessary pesticide use while enhancing the effectiveness of pest management (108).

2.5.2Sustainability Benefits of IPM: The successful large-scale implementation of Integrated Pest Management (IPM) during the mid-1990s marked a significant milestone in demonstrating its sustainability benefits. Through the Pilot Unit strategy, IPM was effectively adopted in crops such as potato, sweet potato, and asparagus, providing early evidence that sustainable pest management practices could be successfully implemented on a broad scale. These initiatives highlighted the environmental benefits of reducing pesticide dependence, the economic advantages of improved crop productivity and lower input costs, and the social gains associated with safer working conditions and enhanced farmer participation. Since then, continued advancements in IPM have further strengthened its role as a sustainable approach to crop protection, delivering long-term environmental, economic, and social benefits (109).

A. Environmental Sustainability: Integrated Pest Management (IPM) contributes significantly to sustainable agriculture by emphasizing preventive and non-chemical pest control measures while limiting pesticide use to situations where pest populations exceed established economic thresholds. Through continuous pest monitoring and informed decision-making, IPM minimizes unnecessary chemical interventions without compromising crop productivity. This targeted approach reduces the overall quantity of pesticides applied and encourages the use of selective, low-risk products that are less harmful to non-target organisms, beneficial insects, and human health. A key strength of IPM lies in its integration of cultural, biological, and physical control strategies with the judicious use of environmentally compatible pesticides, including biopesticides, botanical formulations, microbial agents, and semiochemicals. Compared with conventional synthetic pesticides, these alternatives generally exhibit lower toxicity, reduced environmental persistence, and minimal adverse effects on non-target species. Their adoption not only decreases the risk of soil, water, and air contamination but also supports the conservation of natural enemies and pollinators, thereby improving the ecological balance within agricultural systems (110). IPM encourages the conservation and augmentation of indigenous natural enemies by maintaining habitats, alternative food sources, and overwintering sites that support their survival and effectiveness. Enhanced biological control reduces the need for chemical pesticides, contributing to biodiversity conservation and sustainable crop protection.

B. Economic Sustainability: Integrated Pest Management provides a cost-effective and economically sustainable approach to crop protection by optimizing pest control while reducing dependence on expensive chemical pesticides. Its economic benefits stem from lower pest management costs, improved efficiency in the use of agricultural inputs, and increased farm productivity and profitability. By integrating pest surveillance, economic thresholds, and multiple control strategies, IPM enables farmers to select management practices that are both effective and economically viable. A key advantage of IPM is its ability to support informed, data-driven decision-making by considering the economic, environmental, and social consequences of different pest management options. This integrated approach allows farmers to minimize unnecessary expenditures on chemical inputs, reduce production risks, and improve the long-term sustainability and resilience of their farming systems. Consequently, IPM enhances the competitiveness of agricultural production while promoting resource-use efficiency and long-term economic stability (111). IPM improves economic sustainability by promoting cost-effective alternatives to chemical pesticides, such as cultural and biological control methods. It enhances the efficient use of resources, including land, water, and labor, through precision pest management and integration with sustainable farming practices. By reducing pest-related crop losses and lowering input costs, IPM increases productivity, profitability, and the long-term economic resilience of agricultural systems (112).

C. Social Sustainability: IPM contributes to social sustainability by improving food safety and quality through the prioritization of non-chemical pest control methods and the judicious use of pesticides. This approach minimizes pesticide residues in food, reducing potential health risks to consumers while preserving the nutritional value, quality, and shelf life of agricultural produce. In addition, IPM promotes good agricultural practices, including proper sanitation, worker hygiene, and safe postharvest handling, which help reduce microbial contamination and enhance food safety throughout the supply chain. The integration of biopesticides into IPM further enhances food safety by reducing the use of harmful chemical pesticides. This lowers the likelihood of chemical interactions that may increase the virulence of foodborne pathogens or contribute to antimicrobial resistance, thereby supporting safer and more sustainable food production (113).

3. GOVERNMENT INITIATIVES AND POLICY FRAMEWORK IN INDIA

Agriculture is primarily a state subject under the Indian Constitution, giving state governments the authority to design and implement agricultural policies according to their regional needs. Although the central government provides policy direction and financial support, states have the flexibility to adapt or selectively implement centrally sponsored schemes. This decentralized approach is important because India's diverse agro-climatic conditions require location-specific solutions rather than uniform policies. Consequently, the effectiveness of agricultural development depends on strong coordination between the central and state governments. Strengthening cooperative policymaking and regular dialogue between both levels of government is essential for addressing challenges and promoting sustainable agricultural growth (114). According to the central government, agricultural policy in recent years has gradually shifted from prioritizing higher crop production to improving farmers' income and overall economic well-being (115).

Since the Green Revolution of the 1960s, India's agricultural policies have mainly focused on increasing food grain production to ensure food security for its growing population. In recent years, however, the emphasis has shifted towards an income-oriented approach that seeks to enhance farm productivity, lower cultivation costs, and ensure fair prices for agricultural produce, thereby improving farmers' profitability and livelihoods. The following sections attempt to assess the performance of some of the flagship schemes aimed at addressing sustainability issues in agriculture under the Modi government.

A. <u>National Mission for Sustainable Agriculture (NMSA)</u>: NMSA was first envisaged as one of the eight missions outlined under the National Action Plan on Climate Change (NAPCC) proposed in 2008. It is the flagship central government policy that aims to make agriculture sustainable in a comprehensive manner. As a programmatic intervention since 2014-15, the mission aims at, "making agriculture more productive, sustainable, and remunerative and climate resilient by promoting location specific integrated/composite farming systems; soil and moisture conservation measures; comprehensive soil health management; efficient water management practices and mainstreaming rainfed technologies". (115).
B. <u>Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)</u>: PMKSY is another much publicised central government scheme that focuses specifically on expanding the irrigation infrastructure in the country, particularly to rainfed regions, as well as improving water-use efficiency in agriculture. Launched in 2015, the scheme has four broad components that address specific issues related to water use in agriculture:

- Accelerated Irrigation Benefit Programme (AIBP) - Aimed at faster completion of medium and major irrigation projects.
- Har Khet ko Paani - Promoting minor irrigation, rain water harvesting structures, and developing groundwater in areas of abundance.
- Per Drop More Crop (PDMC) - Expanding micro-irrigation techniques such as drip and sprinkler irrigation that conserve water, and improving water-use efficiency.
- Watershed Development - Revitalising traditional water bodies and managing surface run-off (116)

Activities under the scheme are planned and implemented through District Irrigation Plans (DIP) prepared at the block as well as district levels by taking into account the irrigation requirements of a particular area. Expanding micro-irrigation and improving overall water-use efficiency in agriculture is crucial for a country like India where 80% of available water resources are consumed in agriculture and more than 60% water in irrigated regions goes into water-guzzling crops like paddy and sugarcane.

C. Pradhan Mantri Fasal Bima Yojana (PMFBY): Launched in 2016, PMFBY provides crop insurance coverage to farmers spanning pre-sowing to post-harvest period to offset losses against non-preventable natural risks. The scheme involves use of crop cutting experiments (CCE) to determine crop loss, based on which insurance payouts are made. Earlier, crop insurance schemes in the country were plagued by high premium rates, delays/non-payment of dues, inadequate insurance sums, inadequate government support on subsidies on premiums, low coverage of land area and number of farmers insured (117). PMFBY intends to address these issues by introducing technological interventions such as mobile phone apps for data collection and communication and digitised land records linked to farmers' bank accounts for better settlement of claims (117).

4. CHALLENGES FACED IN ADOPTING MODERN TECHNOLOGY:

Agriculture plays a vital role in India's economy by contributing to national income, generating employment, ensuring food security, and earning foreign exchange. It occupies nearly 51% of the country's land area and remains a key source of livelihood for a large section of the population. Although agriculture's contribution to GDP has declined over the years—from over 56% in the early decades after independence to about 17.4% in 2016–17—it continues to be an important economic sector. Within the agricultural Gross Value Added (GVA), the contribution of the livestock sector has gradually increased, while the share of crop production has declined (118).

A. High population dependence on Agriculture: Agriculture serves as the principal source of livelihood for a significantly larger proportion of India's population than in most other countries. Various surveys and statistical reports indicate that a majority of rural households depend directly or indirectly on agricultural activities for their income and employment. In contrast to developed nations, where only a small fraction of the workforce is engaged in farming, agriculture continues to be the primary occupation for a substantial segment of the Indian population, many of whom have limited alternative employment opportunities. For example, the share of the population involved in agriculture is approximately 5% in Australia, 4% in Canada, 2% in the United Kingdom, 3% in Germany, 9% in Japan, 8% in France, 2% in the United States, 6% in Israel, and 15% in the former Soviet Union. In comparison, nearly 52% of India's population is dependent on agriculture for its livelihood, underscoring the sector's crucial role in supporting employment, rural development, and the national economy (119).
B. Dominance of food crops: Food crops occupy the largest share of India's cultivated land, accounting for nearly 82% of the total sown area. This reflects the country's continued emphasis on ensuring food security and meeting the dietary needs of its large population.
C. *Small and large land holdings*: Small landholdings are prevalent across most regions of India. One observes holdings ranging from less than one acre to between one and five acres, and between five and ten acres (120).
D. Low yield: Despite being one of the world's leading agricultural producers, India's crop productivity remains comparatively low when measured against many other countries. Based on 2008 estimates, India ranked third globally in total food grain production, following China and the United States, with an output

of approximately 267 million tonnes. The country was the second-largest producer of both wheat and rice after China and contributed about 21.6% of global pulse production, making it the world's leading producer of pulses. India also ranked second in groundnut production after China, third in rapeseed production after Canada and China, and second in the production of fruits and vegetables. In addition, it was the second-largest producer of sugarcane after Brazil and among the leading producers of tea and coffee worldwide. Although India occupies a prominent position in global agricultural production, its crop yields per unit area remain relatively low, posing a major challenge to ensuring food security and meeting the demands of its growing population.

E. Lack of modern agricultural knowledge among Indian farmers:A large proportion of Indian farmers have limited financial resources and restricted access to education, which affects the adoption of improved agricultural practices. Many continue to rely on traditional cultivation methods and conventional farming tools rather than modern technologies. As a result, scientific farming techniques are not widely practiced in several regions, leading to lower agricultural productivity. Inadequate technical knowledge, limited extension services, and slow adoption of advanced farming methods have contributed to the relatively slow growth of crop production in the country(121).

F. Lack of Transport and Communication Facilities: In many rural regions of India, inadequate road infrastructure and limited communication facilities continue to hinder agricultural development. During the monsoon season, unpaved village roads often become flooded and muddy, disrupting connectivity with nearby towns and markets. As a result, farmers face considerable difficulties in transporting their produce, leading to increased post-harvest losses, higher transportation costs, and reduced access to markets (122).

G. Lack of Proper Agricultural Planning: Although several agricultural reform plans have been introduced, many have lacked the comprehensive institutional and structural changes needed for effective implementation. As a result, expected improvements in key areas such as irrigation, fertilizer use, and access to quality seeds have not been fully realized. In addition, inadequate planning and execution of policies aimed at strengthening farmers' economic activities have limited their effectiveness, preventing significant improvements in farmers' income and overall socio-economic conditions (123).

CONCLUSION

Agriculture remains the backbone of the Indian economy, supporting food security, employment, rural livelihoods, and overall economic development. However, increasing population pressure, climate change, degradation of natural resources, shrinking landholdings, and environmental concerns have exposed the limitations of conventional farming systems. While traditional agricultural practices have contributed significantly to India's agricultural development, they are no longer sufficient to meet the growing demand for food while ensuring environmental sustainability. Consequently, the adoption of modern technologies and sustainable agricultural practices has become essential for improving productivity, conserving natural resources, and enhancing farmers' livelihoods.

This review highlights the transition from traditional agriculture to modern farming systems that integrate technological innovations with environmentally sustainable practices. Modern approaches such as climate-smart agriculture, organic farming, integrated farming systems, precision farming, and integrated pest and disease management offer practical solutions for addressing the complex challenges faced by the agricultural sector. These approaches promote efficient resource utilization, improve soil health, conserve water, enhance biodiversity, reduce dependence on chemical inputs, and increase the resilience of farming systems against climate variability and biotic stresses. The integration of advanced technologies, including remote sensing, drones, artificial intelligence, biotechnology, Geographic Information Systems (GIS), and data-driven decision-making, further strengthens the efficiency, sustainability, and profitability of agricultural production. Government initiatives and policy interventions have played a significant role in encouraging the adoption of sustainable agricultural practices through financial assistance, technological support, capacity-building programmes, and regulatory measures. Policies promoting soil health management, efficient irrigation systems, digital agriculture, organic farming, climate-resilient agriculture, and integrated farming demonstrate the government's commitment to transforming Indian agriculture into a more sustainable and productive sector. Nevertheless, the effectiveness of these initiatives largely depends on coordinated implementation, institutional support, farmer awareness, and active collaboration among central and state governments, research institutions, extension agencies, and farming communities. Despite considerable progress, several challenges continue to limit the widespread adoption of modern agricultural technologies. Small and fragmented landholdings, inadequate rural infrastructure, limited access to quality inputs and credit, insufficient technical knowledge, low levels of mechanization, digital inequality, and financial constraints remain significant barriers, particularly for small and marginal farmers. Addressing these challenges requires strengthening agricultural extension services, expanding access to affordable technologies, improving rural infrastructure, promoting farmer education and skill development, and encouraging public–private partnerships to facilitate technology dissemination.

Overall, sustainable agriculture represents a balanced approach that combines scientific innovation with ecological conservation to ensure long-term agricultural development. Practices such as crop diversification, crop rotation, conservation tillage, agroforestry, integrated nutrient management, integrated pest management, precision agriculture, and efficient water management collectively contribute to improved productivity, environmental protection, and socio-economic well-being. The integration of these approaches with emerging technologies offers immense potential for building climate-resilient and resource-efficient farming systems.

REFERENCES

1. Finger, R.; Swinton, S.M.; El Benni, N.; Walter, A. Precision Farming at the Nexus of Agricultural Production and the Environment. Annu. Rev. Resour. Econ. 2019, 11, 313–335
2. Addorisio, R.; Spadoni, R.; Maesano, G. Adoption of Innovative for Sustainable Agriculture: A Scoping Review of the System Domain. Sustainability 2025, 17,4224. https://doi.org/10.3390/su17094224)
3. (Reidsma, P.; Accatino, F.; Appel, F.; Gavrilescu, C.; Krupin, V.; Manevska Tasevska, G.; Meuwissen, M.P.M.; Peneva, M.; Severini, S.; Soriano, B. Alternative Systems and Strategies to Improve Future Sustainability and Resilience of Farming Systems across Europe: From Adaptation to Transformation. Land Use Policy 2023, 134, 106881)
4. (Medici, M.; Pedersen, S.M.; Canavari, M.; Anken, T.; Stamatelopoulos, P.; Tsiropoulos, Z.; Zotos, A.; Tohidloo, G. A Web-Tool for Calculating the Economic Performance of Precision Agriculture Technology. Comput. Electron. Agric. 2021, 181, 105930.)
5. (Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., & Godfray, H. C. J. (2013). Sustainable intensification in agriculture: Premises and policies. Science, 341(6141), 33-34.)

6. (Gold, M. V. (2007). Sustainable Agriculture: Definitions and Terms. USDA National Agricultural Library.)
7. (Altieri, M. A. (1999). The Ecological Role of Biodiversity in Agroecosystems. Agriculture, Ecosystems & Environment, 74(1-3), 19-31.)
8. (Pretty, J. N. (1995). Regenerating Agriculture: Policies and Practice for Sustainability and Self-Reliance. Earthscan.)
9. (Dryzek, J. S. (1997). The Politics of the Earth: Environmental Discourses. Oxford University Press.)
10. (Guerrieri, V.; Borchardt, S.; Listorti, G.; Marelli, L.; Vittuari, M. Time to Transform Sustainability Narratives for European Food Systems. Glob. Food Secur. 2025, 44, 100831.)
11. (Osrof, H.Y.; Tan, C.L.; Angappa, G.; Yeo, S.F.; Tan, K.H. Adoption of Smart Farming Technologies in Field Operations: A Systematic Review and Future Research Agenda. Technol. Soc. 2023, 75, 102400.)
12. (Amiri-Zarandi, M.; Dara, R.A.; Duncan, E.; Fraser, E.D.G. Big Data Privacy in Smart Farming: A Review. Sustainability 2022, 14, 9120.)
13. (Gemtou, M.; Kakkavou, K.; Anastasiou, E.; Fountas, S.; Pedersen, S.M.; Isakhanyan, G.; Erekalo, K.T.; Pazos-Vidal, S. Farmers' Transition to Climate-Smart Agriculture: A Systematic Review of the Decision-Making Factors Affecting Adoption. Sustainability 2024, 16, 2828.).
14. (FAO. (2013). Climate Smart Agriculture Sourcebook. Food and Agriculture Organization of the United Nations.)
15. (Herath,S.; Mohri.H.; Wong,P.; Mishra,B.; Sampath,D.S.; Weerakoon,S.B.; Atapattu,S.; Woldie,D. (2013). Traditional and Modern Agriculture Mosaic System for Improving Resilience to Global Change. Institute for Sustainability and Peace. 129)
16. (Princy,D. A Comparative study of Modern and Traditional Agricultural System in India. International Journal of Novel Research and Development. 7(8) ISSN: 2456-4184)
17. Oelbermann M, Voroney RP, Gordon AM (2004) Carbon sequestration in tropical and temperate agroforestry systems: a review with examples from Costa Rica and southern Canada. Agric Ecosyst Environ 104(3):359–377
18. Coulibaly JY, Chiputwa B, Nakelse T, Kundhlande G (2017) Adoption of agroforestry and the impact on household food security among farmers in Malawi. Agric Syst 155:52–69
19. Abbas F, Hammad HM, Fahad S, Cerdà A, Rizwan M, Farhad W, Bakhat HF (2017) Agroforestry: a sustainable environmental practice for carbon sequestration under the climate change scenarios—a review. Environ Sci Pol 24(12):11177–11191

20. Verchot LV, Van Noordwijk M, Kandji S, Tomich T, Ong C, Albrecht A, Palm C (2007) Climate change: linking adaptation and mitigation through agroforestry. Mitig Adapt Strat Glob Change 12(5):901–918
21. Reis GL, Lana ÂMQ, Maurício RM, Lana RMQ, Machado RM, Borges I, Neto TQ (2010) Influence of trees on soil nutrient pools in a silvopastoral system in the Brazilian Savannah. Plant Soil 329(1-2):185–193
22. Dury J, Schaller N, Garcia F, Reynaud A, Bergez JE (2012) Models to support cropping plan and crop rotation decisions: a review. Agron Sustain Dev 32(2):567–580
23. Huang M, Shao M, Zhang L, Li Y (2003) Water use efficiency and sustainability of different longterm crop rotation systems in the Loess Plateau of China. Soil Till Res 72(1):95–104
24. Singh R, Singh GS (2017) Traditional agriculture: a climate-smart approach for sustainable food production. Energy Environ Sci 2(5):296–316
25. Ning C, Qu J, He L, Yang R, Chen Q, Luo S, Cai K (2017) Improvement of yield, pest control and Si nutrition of rice by rice-water spinach intercropping. Field Crops Res 208:34–43
26. Shava S, O'Donoghue R, Krasny ME, Zazu C (2009) Traditional food crops as a source of community resilience in Zimbabwe. Int J Afr Renaiss Stud 4(1):31–48
27. Wang Q, Li Y, Alva A (2010) Cropping systems to improve carbon sequestration for mitigation of climate change. J Environ Prot 1(03):207
28. Kumara PR, Munasinghe ES, Rodrigo VHL, Karunaratna AS (2016) Carbon footprint of rubber/ sugarcane intercropping system in Sri Lanka: a case study. Proc Food Sci 6:298–302
29. Duchene O, Vian JF, Celette F (2017) Intercropping with legume for agroecological cropping systems: complementarity and facilitation processes and the importance of soil microorganisms: a review. Agric Ecosyst Environ 240:148–161
30. Singh R, Singh GS (2017) Traditional agriculture: a climate-smart approach for sustainable food production. Energy Environ Sci 2(5):296–316
31. Latati M, Aouiche A, Tellah S, Laribi A, Benlahrech S, Kaci G, Ounane SM (2017) Intercropping maize and common bean enhances microbial carbon and nitrogen availability in low phosphorus soil under Mediterranean conditions. Eur J Soil Biol 80:9–18
32. Forte A, Fagnano M, Fierro A (2017) Potential role of compost and green manure amendment to mitigate soil GHGs emissions in Mediterranean drip irrigated maize production systems. J Environ Manag 192:68–78

33. Dabney SM, Delgado JA, Reeves DW (2001) Using winter cover crops to improve soil and water quality. Commun Soil Sci Plant Anal 32:1221–1250.
34. Alvarez R, Steinbach HS, De Paepe JL (2017) Cover crop effects on soils and subsequent crops in the pampas: a meta-analysis. Soil Till Res 170:53–65
35. Cooper RJ, Aziza JH, Hiscocka KM, Lovetta AA, Dugdalea SJ, Su ̈nnenberga G, Noble L, Beamish J, Hovesen P (2017) Assessing the farm-scale impacts of cover crops and noninversion tillage regimes on nutrient losses from an arable catchment. Agric Ecosyst Environ 237:181–193
36. Robačer M, Canali S, Kristensen HL, Bavec F, Mlakar SG, Jakop M, Bavec M (2016) Cover crops in organic field vegetable production. Sci Hortic 208:104–110
37. Pinto P, Long MEF, Pineiro G (2017) Including cover crops during fallow periods for increasing ecosystem services: is it possible in croplands of Southern South America? Agric Ecosyst Environ 248:48–57
38. Dabney SM, Delgado JA, Reeves DW (2001) Using winter cover crops to improve soil and water quality. Commun Soil Sci Plant Anal 32:1221–1250. https://doi.org/10.1081/CSS-100104110
39. Onwosi CO, Igbokwe VC, Odimba JN, Eke IE, Nwankwoala MO, Iroh IN, Ezeogu LI (2017). Composting technology in waste stabilization: on the methods, challenges and future pros- pects. J Environ Manag 190:140–157
40. Forte A, Fagnano M, Fierro A (2017) Potential role of compost and green manure amendment to mitigate soil GHGs emissions in Mediterranean drip irrigated maize production systems. J Environ Manag 192:68–78
41. Zhang QC, Shamsi IH, Xu DT, Wang GH, Lin XY, Jilani G, Hussain N, Chaudhry AN (2012). Chemical fertilizer and organic manure inputs in soil exhibit a vice versa pattern of microbial community structure. Appl Soil Ecol 57:1–8
42. Hamadani H, Parrah JD, Hassan N, Dar RA, Sheikh FD (2020) Study of the socioeconomic status of women vermicompost-producing farmers in Kashmir Valley. Int J Curr Microbiol Appl Sci 9(4):1486–1491
43. Sreenivas, A.V.; Rashmi, B.S (2021) The impact of modern ways of farming on agriculture production. AIRO Journals. 4(2). ISSN: 2320-3714
44. Bonaudo, T., Bendahan, A. B., Sabatier, R., Ryschawy, J., Bellon, S., Leger, F., & Tichit, M. (2014). Agroecological principles for the redesign of integrated crop-livestock systems. European Journal of Agronomy, 57, 43-51.

45. Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., & David, C. (2009). Agroecology is a science, a movement, and a practice. A review. Agronomy for Sustainable Development, 29, 503-515.
46. Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer, P, Burlingame B, Dawkins M, Dolan L, Fraser D. Sustainable intensification in agriculture: Premises and policies. Science. 2013;341: 33-34.
47. Newell, P.; Taylor, O.G,; Contested landscapes: The global political economy of climate smart agriculture. Journal of Peasant Studies. 2018;45(1):108-129.
48. Sahu, G,; Rout, P.P,; Mohapatra, S,; Das, S.P,; Pradhan,P.P. (2020). Climate smart agriculture: A new approach for sustainable intensification. Current journal of applied science and technology.39(23): 138-147, 2020; ISSN: 2457-1024
49. Lal R, Delgado J, Groffman P, Millar N, Dell C, Rotz A. Management to mitigate and adapt to climate change. J. Soil Water Conserv. 2011; 66:276–285.
50. Ghosh M. Climate-smart agriculture, productivity and food security in India. Journal of Development Policy and Practice. 2019;1-22.
51. Aggarwal P, Zougmore R, Kinyangi J. Climate-smart villages: A community approach to sustainable agricultural development. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark; 2013.
52. Khatri-Chhetri A, Aggarwal PK, Joshi PK, Vyas S. Farmers' prioritization of climate- smart agriculture (CSA) technologies. Agricultural Systems. 2017;151:184–191.
53. Dadhich CL. Problems and perspectives of financing of smart agriculture in India. In K. R. Gupta and V. B. Angadi (Eds.): Smart Farming – Problems and Prospects. 2017;11–25.
54. Rigby, D., & Cáceres, D. (2001). Organic farming and the sustainability of agricultural systems. Agricultural Systems, 68(1), 21-40.
55. Lampkin, N. (1994). Organic Farming: Sustainable Agriculture in Practice. In Sustainable Agriculture:
Green Fights for the Future, 56-70.
56. Murmu, K., Das, P., Sarkar, A., Bandopadhyay, P., 2022. Organic agriculture: as a climate change adaptation and mitigation strategy. Zeichen J. 8 (3), 171–187.
57. Gamage, A,; Gangahagedara, R,; Gamage, J,; Jayasinghe, N,; Kodikara, N,; Kodikara, P,; Merah, O. (2023). Farming System. Elsevier. DOI: https://doi.org/10.1016/j.farsys.2023.100005

58. Seufert, V., Ramankutty, N., Mayerhofer, T., 2017. What is this thing called organic? – How organic farming is codified in regulations. Food Pol. 68, 10–20. https://doi.org/ 10.1016/j.foodpol.2016.12.009
59. Baker, B.P., Cooley, D., Futrell, S., Garling, L., Gershuny, G. Green, Thomas, A., Moyer, J., Rajotte, E.G., Seaman, A.J., Young, S.L., 2015. Organic Agriculture and Integrated Pest Management: Synergistic Partnership Needed to Improve the Sustainability of Agriculture and Food Systems, vol. 49. https://doi.org/10.13140/RG.2.1.3616.8085.
60. Chojnacka, K., Skrzypczak, D., Szopa, D., Izydorczyk, G., Moustakas, K., WitekKrowiak, A., 2023. Management of biological sewage sludge: fertilizer nitrogen recovery as the solution to fertilizer crisis. J. Environ. Manag. 15 (326), 116602. https://doi.org/10.1016/j.jenvman.2022.116602.Epub2022
61. Correa, R.S., Barbosa, J.Z., Poggere, G.C., Ederlan Magri, E., de Oliveira, S.A., 2023. Grain and foliar nutritional responses of corn (Zea mays L.) to sewage sludge soil application. Waste. Biomass Valorization. https://doi.org/10.1007/s12649-023- 02037-3.
62. Khan, M.J., Qasim, M.S., Umar, M., 2006. Utilization of sewage sludge as organic fertilizer in sustainable agriculture. J. Appl. Sci. 6 (3). https://doi.org/10.3923/ jas.2006.531.535.
63. Seleiman, M.F., Santanen, A., M€akel€a, P.S.A., 2020. Recycling sludge on cropland as fertilizer – advantages and risks. Resour. Conserv. Recycl. 155, 104647. https://doi.org/10.1016/j.resconrec.2019.104647.
64. Rathod, P.H., Patel, J.C., Jhala, A.J., 2011. Potential of gamma irradiated sewage sludge as fertilizer in radish: evaluating heavy-metal accumulation in sandy loam soil. Commun. Soil Sci. Plant Anal. 42 (3), 263–282. https://doi.org/10.1080/ 00103624.2011.538880
65. Kukreti, A., Kurmanchali, N., Rawat, L., 2021. Organic farming and biochar. In: Uniyal, A., Sharma, I. (Eds.), Trends in Agriculture: Traditional and Modern Approaches, pp. 141–153.
66. Zhang, Z., Dong, X., Wang, S., Xiaozhen Pu, X., 2020. Benefits of organic manure combined with biochar amendments to cotton root growth and yield under continuous cropping systems in Xinjiang, China. Sci. Rep. 10, 4718. https://doi.org/10.1038/s41598-020-61118-8.
67. Gamage, A., Basnayake, B., De Costa, J., Merah, O., 2022. Effects of rice husk biochar coated urea and anaerobi-cally digested rice straw compost on the soil fertility, and cyclic effect of phosphorus. Plants 11, 75. https://doi.org/10.3390/plants11010075.
68. Kumar, R., Kumawat, N., Sahu, Y.K., 2017. Role of biofertilizers in agriculture. Pop. Kheti 5 (4), 63–66. https://www.researchgate.net/publication/323185331.

69. Atere, C.T., Olayinka, A., 2012. Effect of organo-mineral fertilizer on soil chemical properties, growth and yield of soybean. Afr. J. Agric. Res. 7 (37), 5208–5216. https://doi.org/10.5897/AJAR11.1378.
70. Mushi, G.E., Di Marzo Serugendo, G., Burgi, P.-Y., 2022. Digital technology and services for sustainable agriculture in Tanzania: a literature review. Sustainability 14, 2415. https://doi.org/10.3390/su14042415.
71. Panwar, A. S., Ravisankar, N., Singh, R., Prusty, A. K., Shamim, M., Ansari, M. A., & Noopur, K. (2021). Potential integrated farming system modules for diverse ecosystems of India. Indian Journal of Agronomy, 66(5th IAC Special issue): S15-S32
72. Singh J. P., Gangwar B., Kochewad S. A., Pandey D. K. (2012): Integrated farming system for improving livelihood of small farmers of western plain zone of Uttar Pradesh, India. SAARC Journal of Agriculture, 10(1), 45-53.
73. Titi, A. L., Boller, E. F., & Gendrier, J. P. (1993). Integrated production principles and technical guidelines. International Organization for Biological and Integrated Control (IOBC). https://iobc-wprs.org/product/iobc-wprs-bulletin-vol-16-1- 1993/
74. Kumar, S., Bhatt, B. P., Dey, A., Shivani, S., Kumar, U., Idris, MD., Mishra, J. S., & Kumar, S. (2018). Integrated farming system in India: current status, scope and future prospects in changing agricultural scenario. Indian Journal of Agricultural Sciences, 88(11), 1661-1675. https://doi.org/10.56093/ijas.v88i11.84880
75. Mahapatra, I. C. (1994). Farming system research– a key to sustainable agriculture. Fertilizer News, 39(11), 13–25.
76. Bhagat, R., Walia, S. S., Sharma, K., Singh, R., Singh, G., & Hossain, A. (2024). The integrated farming system is an environmentally friendly and cost-effective approach to the sustainability of agri-food systems in the modern era of the changing climate: a comprehensive review. Food and Energy Security, 2024(13), e534. https://doi.org/10.1002/fes3.534
77. Fatima, A., Singh, V. K., Babu, S., Singh, R. K., Upadhyay, P. K., Rathore, S. S., Kumar, B., Hasanain, M., & Parween, H. (2023). Food production potential and environmental sustainability of different integrated farming system models in northwest India. Frontiers in Sustainable Food Systems, 7, 959464. https://doi. org/10.3389/fsufs.2023.959464
78. Walia, S. S., & Kaur, N. (2013). Integrated farming system-an ecofriendly approach for sustainable agricultural environment-a review. Greener Journal of Agronomy, Forestry and Horticulture, 1(1), 1–11.

79. Bhagat, R., Walia, S. S., Sharma, K., Singh, R., Singh, G., & Hossain, A. (2024). The integrated farming system is an environmentally friendly and cost-effective approach to the sustainability of agri-food systems in the modern era of the changing climate: a comprehensive review. Food and Energy Security, 2024(13), e534. https://doi.org/10.1002/fes3.534
80. Paramesh, V., Ravisankar, N., Behera, U., Arunachalam, V., Kumar, P., Solomon Rajkumar, R., Dhar Misra, S., Mohan Kumar, R., Prusty, A. K., Jacob, D., & Panwar, A. S. (2022). Integrated farming system approaches to achieve food and nutritional security for enhancing profitability, employment, and climate resilience in India. Food and Energy Security, 11(2), e321. https://doi.org/10.1002/fes3.321
81. Ribeiro, R. H., Ibarr, M. A., Besen, M. R., Bayer, C., & Piva, J. T. (2020). Managing grazing intensity to reduce the global warming potential in integrated crop–livestock systems under no-till agriculture. European Journal of Soil Science, 71(6), 1120–1131. https://doi.org/10.1111/ejss.12904
82. Paramesh, V., Ravisankar, N., Behera, U., Arunachalam, V., Kumar, P., Solomon Rajkumar, R., Dhar Misra, S., Mohan Kumar, R., Prusty, A. K., Jacob, D., & Panwar, A. S. (2022). Integrated farming system approaches to achieve food and nutritional security for enhancing profitability, employment, and climate resilience in India. Food and Energy Security, 11(2), e321. https://doi.org/10.1002/fes3.321
83. Clark, M.S., & Gage, S. H. (1996). Effects of free-range chickens and geese on insect pests and weeds in an agroecosystem. American Journal of Alternative Agriculture 11(1), 39–47. https://doi.org/10.1017/S0889189300006718
84. Dasgupta, P., Goswami, R., Ali, Md. N., Chakraborty, S., & Saha, S. K. (2015). Multifunctional role of integrated farming system in developing countries. International Journal of Bio-resource and Stress Management, 6(3), 424-432. https://ojs.pphouse.org/index.php/IJBSM/article/view/717
85. Sharma, D. K. (2021). Integrated farming system: an approach for sustainable management of natural resources. Journal of Natural Resource Conservation and Management, 2(1), 1-5. https://doi.org/10.51396/ANRCM.2.1.2021.1-5
86. Gulaiya, S., Kumar, M., Kumar, R., Kumar, R., Singh, N., Yadav, K., & Rajpoot, A. S. (2024). Regenerative agriculture: Integrating soil health, carbon management and socio-ecological outcomes. Int. J. Environ. Clim. Change, 14, 92-105.

87. Raj, P., Sharma, S., Kapri, A., & Gulaiya, S. (2025). Precision Agriculture: A Strategic Approach to Resource Efficiency and Sustainable Farming. Journal of Scientific Research and Reports, 31(8), 382-391.
88. Auernhammer, H. (2001). Precision farming – the environmental challenge. Computers and Electronics in Agriculture, 30, 31– 43.
89. Hakkim, V. M. A., Joseph, E. A., Gokul, A. J. and Mufeedha, K. (2016). Precision farming: The future of Indian agriculture. Journal of Applied Biology & Biotechnology, 4(3), 68–72.
90. Kumari, Ankita, Uzma Manzoor, Sahadeva Singh, Mahendra Anjna, Ravi Kumar, Shikha Arya, Shubham Ahirwar, Shani Gulaiya, and S K Goyal. 2026. "Precision Agriculture for Sustainable Crop Production: A Transformative Technological Approach". Journal of Experimental Agriculture International 48 (1):627-38. https://doi.org/10.9734/jeai/2026/v48i14035.
91. McBratney, A., Whelan, B., Ancev, T. and Bouma, J. (2005). Future directions of precision agriculture. Precision Agriculture, 6, 7–23
92. Mandal, S. K. and Maity, A. (2013). Precision farming for small agricultural farms: Indian scenario. American Journal of Experimental Agriculture, 3(1), 56–77
93. Atzberger, C. (2013). Advances in remote sensing of agriculture: Context description, existing operational monitoring systems and major information needs. Remote Sensing, 5, 949–981
94. Alazzai, W. K., Abood, B. Sh. Z., Al-Jawahry, H. M. and Obaid, M. K. (2024). Precision farming: The power of AI and IoT technologies. E3S Web of Conferences, 491, 04006
95. Gebbers, R., & Adamchuk, V. I. (2010). Precision agriculture and food security. Science, 327(5967), 828-831
96. Angon, P. B.; Mondal, S.; Jahan, I.; Datto, M.; Antu, U. B.; Ayshi, F. J.; Islam, M. S. Integrated pest management (IPM) in agriculture and its role in maintaining ecological balance and biodiversity. Advances in Agriculture 2023, 2023 (1), No. 5546373.
97. Rossi, V.; Caffi, T.; Salotti, I.; Fedele, G. Sharing decision- making tools for pest management may foster implementation of Integrated Pest Management. Food Security 2023, 15 (6), 1459−1474.
98. Scheff, D. S.; Phillips, T. W. Integrated pest management. In Storage of Cereal Grains and Their Products; Elsevier, 2022; pp 661− 675.

99. Szyniszewska, A. M.; Akrivou, A.; Björklund, N.; Boberg, J.; Bradshaw, C.; Damus, M.; Gardi, C.; Hanea, A.; Kriticos, J.; Maggini, R.; et al. Beyond the present: How climate change is relevant to pest risk analysis. EPPO Bulletin 2024, 54, 20−37.

100. Zhou, W.; Arcot, Y.; Medina, R.F.; Bernal, J.; Zevallos, L.C.; Akbulut, M.E.S. Integrated Pest Management : An Update on the Sustainability Approach to Crop Protection. ACS Omega 2024. 9, 41130-41147. https://doi.org/10.1021/acsomega.4c06628

101. Choudhury, D.; Kumar, P.; Zhimo, V. Y.; Sahoo, J. Crop rotation patterns and soil health management. In Bioremediation of Emerging Contaminants from Soils; Elsevier, 2024; pp 565−589.

102. Huss, C.; Holmes, K.; Blubaugh, C. Benefits and risks of intercropping for crop resilience and pest management. Journal of economic entomology 2022, 115 (5), 1350−1362.

103. Kruidhof, H. M.; Elmer, W. H. Cultural methods for greenhouse pest and disease management. Integrated Pest and Disease Management in Greenhouse Crops 2020, 285−330.

104. Pinto, C. B.; Carmo, D. d. G. d.; Santos, J. L. d.; Filho, M. C. P.; Soares, J. M.; Sarmento, R. A.; Lima, E.; Bacci, L.; Picanço, M. C. Sampling Methodology of a Key Pest: Technique and Sampling Unit for Evaluation of Leafhopper Dalbulus maidis Populations in Maize Crops. Agriculture 2023, 13(7), 1391.

105. Batz, P.; Will, T.; Thiel, S.; Ziesche, T. M.; Joachim, C. From identification to forecasting: the potential of image recognition and artificial intelligence for aphid pest monitoring. Frontiers in Plant Science 2023, 14, DOI: 10.3389/fpls.2023.1150748.

106. Monticelli, L. S.; Bishop, J.; Desneux, N.; Gurr, G. M.; Jaworski, C. C.; McLean, A. H.; Thomine, E.; Vanbergen, A. J. Multiple global change impacts on parasitism and biocontrol services in future agricultural landscapes. In Advances in Ecological Research, Vol. 65; Elsevier, 2021; pp 245−304.

107. Fatouros, N.; Cusumano, A.; Bin, F.; Polaszek, A.; Van Lenteren, J. How to escape from insect egg parasitoids: a review of potential factors explaining parasitoid absence across the Insecta. Proceedings of the Royal Society B 2020, 287 (1931), No. 20200344.

108. Han, P.; Rodriguez-Saona, C.; Zalucki, M. P.; Liu, S.-s.; Desneux, N. A theoretical framework to improve the adoption of green Integrated Pest Management tactics. Communications Biology 2024, 7 (1), 337.

109. Cisneros, F.; Gregory, P. Potato pest management. Aspects of Applied Biology 1994, 39, 113−124.

110. Busch, A. K.; Douglas, M. R.; Malcolm, G. M.; Karsten, H. D.; Tooker, J. F. A high-diversity/IPM cropping system fosters beneficial arthropod populations, limits invertebrate pests, and produces competitive maize yields. Agriculture, ecosystems & environment 2020, 292, No. 106812.

111. Wyckhuys, K.; Sanchez-Bayo, F.; Aebi, A.; van Lexmond, M. B.; Bonmatin, J.-M.; Goulson, D.; Mitchell, E. Stay true to integrated pest management. Science 2021, 371 (6525), 133−133.

112. Junaid, M.; Gokce, A. Global agricultural losses and their causes. Bulletin of Biological and Allied Sciences Research 2024, 2024 (1), 66−66.

113. Fenibo, E. O.; Ijoma, G. N.; Matambo, T. Biopesticides in sustainable agriculture: Current status and future prospects. New and future development in biopesticide research: Biotechnological exploration
2022, 1−53.

114. OECD/ICRIER, (2018). Agricultural Policies in India. OECD Food and Agricultural Reviews. OECD Publishing: Paris. https://www.oecd-ilibrary.org/docserver/9789264302334-en.pdf?expires=1589787765&id=id&accname=guest&checksum=73A3C0047EEF0B6036D9A83A72CB267B

115. Ministry of Agriculture and Farmers Welfare, (2019). Annual Report 2018-19. Government of India. http://agricoop.nic.in/sites/default/files/AR_2018-19_Final_for_Print.pdf

116. PMKSY (n.d.). Operational Guidelines of Pradhan Mantri Krishi Sinchayee Yojana. https://pmksy.gov.in/pdflinks/Guidelines_English.pdf

117. Gulati, Ashok, Prerna Terway and Siraj Hussain, (2018). "Crop Insurance in India: Key Issues and Way Forward". Working Paper No. 352. ICRIER: New Delhi. http://icrier.org/pdf/Working_Paper_352.pdf

118. Abraham, M., & Pingali, P. (2020). Transforming smallholder agriculture to achieve the SDGs. In The role of smallholder farms in food and nutrition security (pp. 173-209).

119. Boretti, A., & Rosa, L. (2019). Reassessing the projections of the world water development report. NPJ Clean Water, 2(1): 1-6.

120. .Brausmann, A., & Bretschger, L. (2018). Economic development on a finite planet with stochastic soil degradation. European Economic Review, 108: 1-19.

121. Chakraborty, D. (2018). IoT & Agricultural Marketing: A Case Study. International Journal of Research, 9(1).

122. Bateman, A. M., & Muñoz-Rojas, M. (2019). To whom the burden of soil degradation and management concerns. In Advances in Chemical Pollution. Environmental Management and Protection, 4: 1-22).

123. Bhatt, H., Bhushan, B., & Kumar, N. (2019). IOT: the Current Scenario and Role of Sensors Involved in Smart Agriculture. International Journal of Recent Technology and Engineering, 8(4), 12011-12023.