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Advancing Modern Agriculture: Integrating Sustainable Practices for a Resilient Future

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ABSTRACT

Modern agriculture faces serious challenges due to the increasing demand for food and climate change. Sustainable agricultural practices (SAPs) offer critical solutions to these challenges by enhancing efficiency, promoting ecological balance, and ensuring the long-term food security. SAPs, such as climate-smart agriculture, regenerative agriculture, precision agriculture, organic farming, integrated pest management, diverse crop rotation, and integrated nutrient management, once integrated into modern agriculture, will ensure global food security, protection of biodiversity, and sustainable crop production in the face of rapid population growth. This review discusses SAPs as a solution to the problems of modern agriculture and emphasizes the importance of interdisciplinary approaches and policy support for a food-secure future.

Keywords: Climate-smart agriculture, Regenerative agriculture, Precision agriculture, Integrated pest management, Diverse crop rotation

Introduction

Since the dawn of the green revolution, crop yields have almost doubled,¹ but with the increasing human population, crop yields are now falling short of meeting the demand for food.² The world will need 70–100% more food production by 2050.³ Today, the increasing global population is resulting in severe pressure on limited natural resources, and humans are exhausting their natural resources in a way that could result in the depletion of these natural resources for future generations. Hence, with the growing population, it has become more urgent to adopt sustainable agricultural practices to secure natural resources for future generations.⁴ The extensive use of agrochemicals is resulting in soil loss, increasing demand for water, and environmental pollution, consequently affecting overall biodiversity and resulting in the emission of greenhouse gases.³ In the future, agriculture will need to ensure a sustainable food supply by using resources efficiently and with less land available to meet the increasing global demand for food.⁵ Promoting sustainable agriculture practices (SAPs) at the individual farmer level is becoming increasingly crucial.⁶

The implementation of SAPs in agriculture requires integrating more efficient, productive, and competitive practices while securing the environment and socioeconomic factors of local communities as well.⁷ The integration of approaches, such as integrated pest management (IPM), integrated nutrient management (INM), climate-smart agriculture (CSA), organic farming, and precision and dynamic agriculture, have proven to be the best approaches to ensure sustainability in agriculture.⁸ These sustainable agriculture (SA) approaches can be integrated with diverse production

technologies and agroclimatological conditions. Although there may be a difference in the scope of each approach, one thing is common: all these approaches are options for the farmers and will strongly influence how they manage their farm resources in the long run.⁸

Keeping in view the current condition of a growing population and problems of food security, it has become more urgent than ever before to integrate sustainable agriculture practices into modern agriculture to safeguard natural food resources for future generations. This review explains the opportunities and challenges associated with the integration of these sustainable agriculture practices in modern agriculture (Figure 1).

What Does Sustainability Mean in Agriculture?

The idea of sustainability has come to notice since the publication of the Brundtland Report in 1987.⁹ The concept of sustainability was first applied in the field of forestry, where the principle of “never to harvest more than the yield of forest per annum” was applied.¹⁰ Keeping in view the complex nature of sustainable agriculture, it is complicated to explain it in a single definition. Due to this fact, several definitions have emerged, which can be a good thing as these definitions can be integrated, but they can still be harmful as well, as one definition can also serve against the other.¹¹ Here are some of the most common viewpoints about sustainable agriculture: sustainable agriculture is the integrated system of animal and plant production practices that, in the long run, provide food and fiber for humans, ensure the quality of the environment, make efficient use of farm non-renewable resources, integrate natural biological controls and cycles, consequently enhancing farmers’ quality of life by providing economic stability.¹²

It is crucial to understand that, for a farm to ensure sustainability, it must guarantee adequate food production, protect natural resources, and be environmentally friendly while staying profitable. A sustainable farm must rely on natural resources and cycles produced at the farm rather than the purchased inputs.¹³ Sustainable agriculture is a set of practices that integrate natural processes to conserve resources while minimizing waste and its impact on the environment. It promotes resilience, self-regulation, and sustained production in agriculture to nourish all.¹⁴

Taking an interdisciplinary approach helps bridge the gap between these modern definitions and evolving concepts.

Modern Sustainable Practices in Agriculture

With the increasing human population, the integration of these modern sustainable practices is becoming crucial to sustain the adequate food production. It is

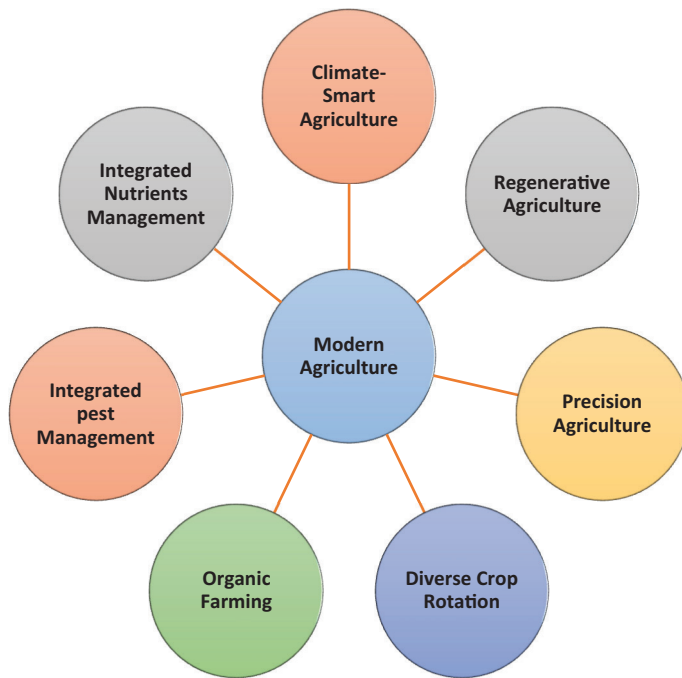


Fig 1 | Integration of sustainable agriculture practices in the modern agriculture system

beyond the scope of this paper to explain the integration of all sustainable agriculture practices. However, the most important and modern practices that are used and to be integrated into the agricultural system are discussed in this review.

Climate Smart Agriculture (CSA)

Owing to the increasing population of the world, the demand for food is also increasing. According to the Food and Agriculture Organization (FAO), by 2050, global food production must increase by 60% to feed this growing population, and climate change is posing a significant threat to the global food security of the future.¹⁵ To mitigate the effects of climate change, the FAO introduced the concept of CSA, which is based on the fundamental principles of sustainable crop improvement, by making crops more resilient to climate change, and also reducing the emission of greenhouse gases from the agriculture sector.¹⁶ CSA is a recent technique that is used today to augment the management of agriculture under climate change. It helps adopt new technologies and practices to boost the production of agriculture by mitigating the challenges posed in the era of climate change.¹⁷ The aim of CSA also includes the emission of greenhouse gases by controlling the plants and soils in a way so that they can absorb the carbon dioxide of the atmosphere, hence acting as carbon sinks.¹⁸ One of the key components of CSA is sustainable intensification to allow maximum utilization of natural resources, as the agriculture sector is highly dependent on environmental factors; hence, improving the adaptability of the crops using CSA practices can improve the yields in the long run.¹⁹ Therefore, CSA can be an effective approach to improving agricultural productivity globally in a sustainable manner under changing climate conditions.²⁰

Still, the term CSA is evolving and in the developing phase, and there is a lack of research on integrating sustainable CSA with modern agriculture. However, to overcome the ever-increasing effect of climate change, it is becoming critical to integrate the practices of CSA into the modern agricultural system.

Regenerative Agriculture (RA)

RA is an integrative approach that provides greater resilience to changing climates. It also helps to restore biodiversity loss and improves the overall health of the soil. It supports the establishment of emerging circular economies and community well-being.²¹ RA mainly focuses on the improvement of biodiversity, water systems, climate change resilience, and soil health.²² RA is proposed as an alternative to food production with lower or positive environmental and social effects.²³ The idea of RA has been of great interest to the stakeholders in the agriculture system, but despite its widespread interest, the term RA is still under-defined and does not have a widely accepted definition.²⁴ It is not a single agriculture practice but a set of integrated sustainable agriculture practices.²⁵

Recycling of agricultural trash and addition of composted material from sources other than farms integrated with agroecology, holistic management, and restoration ecology are the most widely used approaches in RA.²⁶ Key principles common to regenerative farming systems include, but are not limited to, eliminating tillage, actively restoring soil communities, enhancing crop diversity on the farm, and integrating livestock with crop management on the land.²⁷ Hence, the integration of RA can be a sustainable and economical production option for farmers, unlike the implementation of input-intensive crop production models.²⁸ Additionally, RA can also help integrate various farm and soil components to work together, hence contributing to enhancing the overall productivity of the farm. The integration of RA in modern agriculture can be a great option, especially when it comes to the reclamation of soil biodiversity and climate resilience (Figure 2).

Precision Agriculture (PA)

Over the last millennia PA has gained a very high profile. The advent of modern tools of PA has enabled farmers to overcome the variability in agriculture. It is a crop management concept and can be a sustainable option to overcome the social and environmental pressure on agricultural lands.²⁹ PA is a set of modern technologies like sensors, enhanced machinery, modern information systems, and advanced management systems applied to minimize uncertainty in agriculture, allowing the optimum usage of resources. It also helps to minimize the environmental impact of agriculture on the environment while ensuring sustainable food production.³⁰ Site-specific management is an old agricultural concept that involves making the right decisions at the right time and place. This concept is applied in PA by using computational approaches to make the right decisions on farms.³¹

In order to increase overall farm efficiency, massive data is used in PA to make decisions related to

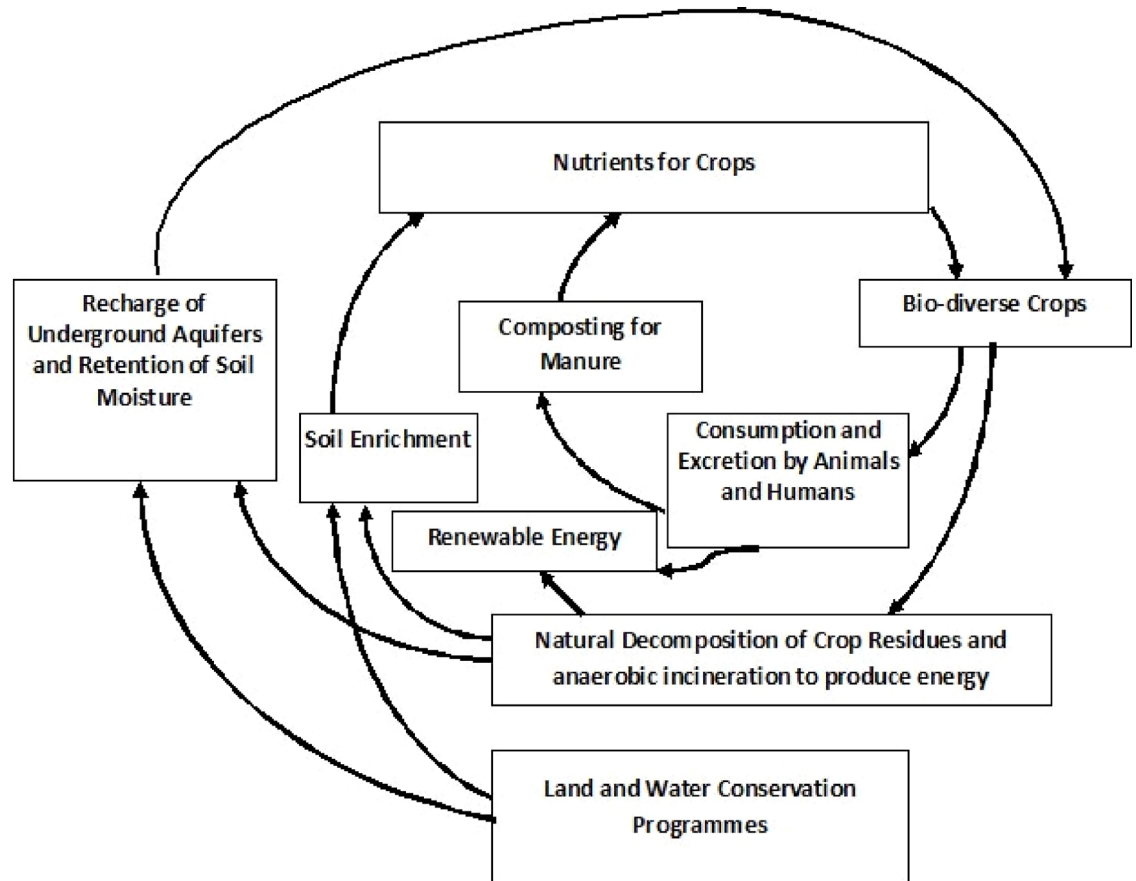


Fig 2 | Integrating sustainable agricultural practices for effective resource management and enhanced crop productivity in modern farming. Attribution: IKPlusOne, CC BY-SA 4.0 via Wikimedia Commons

the utilization of resources and the prediction crop yields and crop quality.³² PA promotes sustainability in agriculture by ensuring the efficient and sustainable usage of resources such as nutrients, agrochemicals, and water while minimizing greenhouse gas emissions and nutrient leaching, consequently minimizing environmental risks.³³ PA supports sustainability by managing farm inputs by applying chemicals or fertilizers only where needed. Hence, PA helps to minimize the excess usage of agrochemicals, and it has been proven on farm trails that PA enhances the overall profitability of the farm while aligning the farm practices in accordance with environmental regulations.³⁴

Although PA is a great option to promote sustainability in agriculture, a lot of work is still required in the field of remote sensing and mapping systems. Moreover, PA practices being information intensive cannot be successfully applied in agriculture until advanced networking and processing powers are developed and applied in agriculture.²⁹

Integrating Organic Farming into Modern Agriculture

Despite its area of only 1%, organic farming is a rapidly growing practice in agriculture.³⁵ It is often proposed as a solution for producing food with minimal environmental impact.³⁶ The concept of a “return to nature” lifestyle became widely embraced. With increasing awareness of the harmful effects of synthetic chemical

inputs in agriculture, organic farming emerged as a promising alternative to conventional methods.³⁷ Maintaining animal and environmental welfare, encouraging sustainable farming practices, utilizing natural fertilizers and eco-friendly methods for pest and disease and weed management, ensuring the production of nutritious food, and avoiding cultivation of GM crops are the key aspects of organic farming.³⁸

Organic farming provides an effective approach to farming as it ensures sustainable yields, enhances the overall health of the soil, and minimizes environmental harm while reducing the reliance on agrochemicals. While other farming methods contribute to addressing environmental concerns, organic farming remains the most scientifically validated and environmentally friendly approach for preserving ecological balance.³⁹ While restricting the use of agrochemicals in most of the countries, most countries overlook the broader application of organic farming for environmental principles. Enhancing the role of organic farming is very crucial in emphasizing the best environmental practices under the restriction of different agrochemicals.³⁵

Hence, due to its wider social and environmental acceptance, organic farming is becoming an effective approach to tackling these challenges. The increasing demand for organic farming products is a great opportunity for the farming community to adopt the practices of organic farming in modern agriculture.⁸

Integrated Pest Management (IPM)

IPM is increasingly adopted by both developing and developed countries. IPM is crucial for sustainable agriculture to achieve eco-friendly and pesticide-free food production. IPM involves a timely and coordinated approach that ensures the control of pests at the primary stage. The agroecosystem analysis (AESA) in IPM monitors crop health by considering the growth stages of the crop, pest dynamics, soil, and climatic conditions. The system uses traps, soil analysis, and pest forecasting for effective intervention planning.⁴⁰ Due to the increase in global pesticide usage, IPM is becoming a sustainable alternative to synthetic pesticides, especially for tropical smallholders. Many studies across 24 countries in 84 IPM projects showed an increase in crop yields by 40.9% and a reduction in usage of pesticides by 30.7% from baseline.⁴¹

Insecticide resistance is becoming a major challenge in sustainable agriculture practices and it is also increasing public concern about the excessive usage of pesticides. Under these public concerns about environmental safety, IPM has emerged as a crucial approach for sustainable pest management. IPM is a combination of biological, chemical, mechanical, and physical approaches to control pests.⁴² The cultivation of insect-resistant varieties is also an effective approach to the sustainable management of insect pests.⁴² The effective integration of these approaches can reduce the usage of pesticides by 50% compared to standard spraying. Hence, IPM can be a great practice to integrate into modern agriculture for the sustainable control of insect pests.

Diverse Crop Rotation for Sustainable Production

Crop rotation plays a crucial role in sustainable crop production by enhancing the overall ecological and soil sustainability it plays a crucial role in reducing incidents of insects, weeds, and diseases, and in improving the physical and chemical structure of soil. It also enhances the water retention capacity of the soil. Additionally, the diverse crop rotation also fosters the health of the soil while ensuring sustainable crop production.⁴³ In contrast to having monoculture or two crops, diversified crop rotation involves the cultivation of 3 or more crop species.⁴⁴ Having diverse crop rotations helps to control pathogen reproduction and insects, thus helping to disrupt their life cycle in a sustainable and environmentally friendly way.⁴⁵ Once certain plant species are integrated into crop rotation, they tend to restore the nutrients of the soil, hence making it a great sustainable practice in agriculture.⁴⁶

Diverse crop rotation maintains the diversity of the cropping system by increasing crop residual matter and diverse root systems of different crops, consequently improving overall soil health and microbial activity.⁴⁷ Due to these benefits, diverse crop rotations are becoming more and more popular tools for maintaining sustainable crop production. It is very crucial to provide policy and organizational support to implement the strategies of crop rotation at the farmer level. The scientific community must work on finding the

best crop rotation practices to ensure the sustainable food production.⁴³

Integrated Nutrients Management (INM)

INM refers to the integration of modern and conventional nutrient management methods into the economically optimal agricultural system, which uses all organic, inorganic, or any other biological options in an integrated manner while ensuring the ecological health of the farm.⁴⁸

Under INM, high nutrient use efficiency is achieved by minimizing the nutrient losses caused by volatilization, leaching, immobilization, runoff, and emission.⁴⁹ Additionally, INM optimizes the health of the soil by improving the overall biological, chemical, physical, and hydrological properties of the soil, consequently enhancing farm productivity.⁵⁰ INM methods are designed in accordance with the input and output of the crop, where the nutrient input matches with the demand of the crop while synchronizing with the stage of crop growth.⁵¹

INM plays a critical role in sustainable crop production by enhancing crop yields by 8–150%. It improves the overall water nutrient use efficiency consequently boosting the economic returns. INM reduces the dependence on synthetic fertilizers and minimizes the land use intensity and greenhouse gas emissions from the agriculture sector while ensuring high productivity. The eco-friendly practices of INM also tend to improve soil health, sustainability, and grain quality, making it a great option for sustainable agriculture.⁵²

Hence, integrating INM practices into modern agriculture can be a significant contributor to ensuring sustainable crop production.

Prospects of Sustainable Agricultural Practices

Sustainable agriculture is a subject of great interest and lively debate in many parts of the world. Most agriculturalists agree that the concept of sustainable agriculture is of great importance to the sustainability of our biosphere and its ever-increasing human population.⁵³

The future of sustainable agriculture lies in technological advancements like precision farming, hydroponics, and biotechnology to boost productivity and reduce environmental impact. CSA practices, such as agroforestry and IPM, will enhance resilience to climate change. Sustainable intensification aims to increase yields without expanding farmland through efficient resource use. Circular economy strategies like composting and bioenergy production can reduce waste and reliance on synthetic fertilizers. Agroecology promotes biodiversity and ecosystem services like soil fertility. Policy support and consumer demand for sustainable, organic, and locally sourced food will further drive the adoption of eco-friendly practices.⁵⁴

Hence integration of these novel agricultural approaches is very crucial for the sustainability of our food and ecological system under the growing human population. Under given circumstances, only radical changes toward sustainable practice can ensure the preservation of nature and its resources for the benefit

of humanity. Therefore, the integration of these sustainable agriculture practices into the modern agriculture system is the most important step that humanity needs to take right now.⁸

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