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Overview of empowering sustainable agriculture through smart farming and regenerative practices

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Abstract

With rapid urbanization and the growing impacts of climate change, agriculture is facing growing pressure as the global population approaches 10 billion. These challenges will need to be addressed by a practice shift from an agricultural standpoint towards sustainability; ensuring that food security and natural resources sustainability is achieved for future generations. This review presents some of the key technologies and strategies that could be embraced by the farmers to ensure sustainable agriculture. The interconnection between smart farming (precision agriculture) and regenerative agriculture is the most important aspect of this sustainable agriculture. Precision agriculture is an application of state-of-the-art technologies such as Internet of Things sensor technologies, drones, data analysis and robotics to get maximum use from inputs, maximize productivity and minimize the environmental footprint. Rather, regenerative practices tend to be more concerned with the healing of soil, biodiversity, and the creation of a resilient agroecosystem. This review highlights the possible integration of these options and the role they can play towards sustainable intensification. Although the results are good, the use of these products is still limited because of the initial high investment costs, the lack of technical knowledge and infrastructural problems. The review stresses the importance of synergy in research, policy development and education in order to deal with these challenges. The available evidence suggests that smart farming and regenerative agriculture address different but complementary dimensions of sustainability. While digital technologies improve resource-use efficiency and precision management, regenerative practices restore ecological functions and enhance system resilience. Their integration therefore represents a more comprehensive strategy for sustainable agricultural intensification than either approach alone, although economic and institutional barriers continue to limit widespread adoption. In conclusion, ecological restoration is an effective way to adopt data-driven innovation as a pathway to environmental sustainability and global food security.

Keywords: Climate change, Regenerative practices, Smart farming, Sustainable agriculture

Abbreviations: AI: Artificial Intelligence; DSS: Decision Support System; GAI: Green Area Index; GHGs: Greenhouse Gases; ICLS: Integrated Crop-Livestock System; IoT: Internet of Things; IPCC: Intergovernmental Panel on Climate Change; ML: Machine Learning; N: Nitrogen; NDVI: Normalized Difference Vegetation Index; RA: Regenerative Agriculture; SPAD: Soil Plant Analysis Development; UAV: Unmanned Aerial Vehicle; VRT: Variable Rate Technology

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Introduction

The rapid pace of climate change, gradual decrease in the agriculture land and the expanding population, are the major issues which need coordinated international response (Noroz et al., 2021; Omokhafe et al., 2024). The world's population is expected to swell to 10 billion by 2050, which means a 70% increase in food production by 2050 (Karunathilake et al., 2023). This emphasizes the importance of sustainable agricultural intensification. Population growth leading to rapid urbanization is turning large areas of arable land into residential and industrial developments. For example, urbanization trend is expected to result in an annual loss of more than 1.6-3.3 million hectares of agricultural land worldwide in the 2000-2030 period (United Nations, 2019). Over-use of conventional practices (including synthetic fertilizers); over-irrigation; monocropping are causing soil health to be degraded, polluting water bodies and causing biodiversity losses. The agriculture sector is responsible for 24% of global GHGs, mostly from the emissions of methane from livestock, nitrous oxide from fertilizers and carbon dioxide from deforestation for crop production (IPCC 2014). If population growth and environmental degradation are not managed well, it may result in very high levels of food insecurity, malnutrition and susceptibility to climate-induced crop failure. By leveraging technologies such as precision agriculture, Internet of Things (IoT) smart sensors, and drone-based monitoring, smart farming can deliver efficient resource utilization, improved crop yields, and fewer environmental impacts.

Moreover, smart farming (precision agriculture) is the use of advanced technologies and data-driven analysis to enhance agriculture productivity, resource use efficiency and sustainability (Karunathilake et al., 2023). Smart farming consists of precision monitoring/ sensors, the Internet of Things (IoT), drones and imaging, artificial intelligence (AI), automated machinery, data and analytics. The technologies offer farmers accurate, real-time information for making informed decisions. This is modern technology that is required for the challenges of the world that we live in today, such as population growth, climate change and resource depletion. Furthermore, Regenerative agriculture (RA) techniques such as no-till, cover cropping and agroforestry can improve soil fertility, sequester carbon and establish resilient agriculture systems. It is a holistic approach that is based on the principles such as minimizing or eliminating tillage practices (which enhances soil health, reduces erosion, improves soil structure, and increases biological activity), protecting soil through cover cropping (which enhances soil biodiversity, water retention and soil organic matter), preserving biodiversity (by reducing synthetic chemical use and heavy mechanization) and implementing integrated livestock management (which enhances soil health, soil fertility and water retention capacity) (McGuire, 2018; Lal, 2020; Newton et al., 2020). The goal of this is to be sustainable, maintain soil health, boost biodiversity, and decrease use of synthetic inputs (Rehberger et al., 2023; Giller, 2021).

We explored the recent development of smart farming and RA and discussed the possibility of how these could revolutionize farming in a sustainable way. We were able to identify the major benefits and barriers of such integration as well as the potential strategies to address the barriers. Moreover, we provided policy suggestions that could ease the implementation of the integrated practices, focusing on the importance of supporting policy structures in research, education and infrastructure development. The shift to sustainable agriculture has to be understood in the broader socio-economic and policy context as well as the technological and ecological aspects. Other structural issues, including access to credit, fewer extension services and low digital literacy, are other constraints faced by smallholder farmers, particularly in developing countries, which are limiting the adoption of advanced agricultural technologies. In the short term, however, low input regenerative systems may be costly to adopt, and the yield may be reduced in the interim, so it may not be possible at first for farmers to adopt this system. Hence, sustainable agricultural transformation must go beyond technology and innovation and be based on a multi-dimensional strategy involving institutional support, financial incentives, and capacity building efforts. This multi-faceted approach assures not only environmental sustainability but also economic and social sustainability.

Smart farming: Innovations for sustainable agriculture

In the ancient times, during the beginning of the agricultural evolution, it was entirely dependent on manpower and animal labor which was the traditional practice to grow crops and was termed as agriculture 1.0. Later, with the advancement and progression of Green Revolution, which began in the mid-20th century, the introduction of high-yield crop varieties and chemical fertilizers transformed agricultural production. Extensive use of chemicals and machinery in agriculture increases productivity but is harmful to our environment and can be termed as agriculture 2.0. Furthermore, the advancements in computation and electronics during the 20th-century led to the introduction of robotic and programmed machinery in agriculture which gave rise to Agriculture 3.0. It has solved most of the agriculture problems, but conservation of resources is still needed. With technological advancement, the introduction of IoT sensors, AI and data analysis leads to agriculture 4.0 known as smart farming. The comparative analysis of smart farming and conventional farming is shown in Table 1. The core objective of Smart farming is to reduce the negative impact of agriculture on the environment and to protect our resources for future generations (Karunathilake et al., 2023). Smart farming includes tools such as IoT, AI, data analytics, drones, and robotics (Fig. 1). It allows farmers to make data-driven decisions, conserve resources, and reduce environmental impacts (Dhanaraju et al., 2022). This innovative approach is increasingly essential for addressing the challenges of modern agriculture, including population growth, climate change, and resource scarcity.

Table 1 Comparative results of smart farming and conventional farming

Crop	Parameter	Smart Farming	Conventional Farming	References
Rice	Nitrogen fertilizer use	11.9% reduction in total N applied per hectare	100% baseline (uniform application)	Ghazali et al. (2020)

Crop	Parameter	Smart Farming	Conventional Farming	References
Rice	Labor efficiency	50% reduction in labor for fertilizer application	Manual labor-intensive methods	Ghazali et al. (2020)
Wheat	Grain yield	12% increase in yield	Farmer's traditional practices	Ahmed et al. (2024)
Wheat	Nitrogen use efficiency	39% improvement in N uptake efficiency	Lower efficiency in farmer practices	Ahmed et al. (2024)
Various	Water use efficiency	50% water savings with IoT-based smart irrigation	Flood irrigation or fixed schedules	Liu et al. (2020)
Various	Weed control	Robotic weeders eliminated herbicide use	Reliance on chemical herbicides	Bechar & Vigneault (2017)

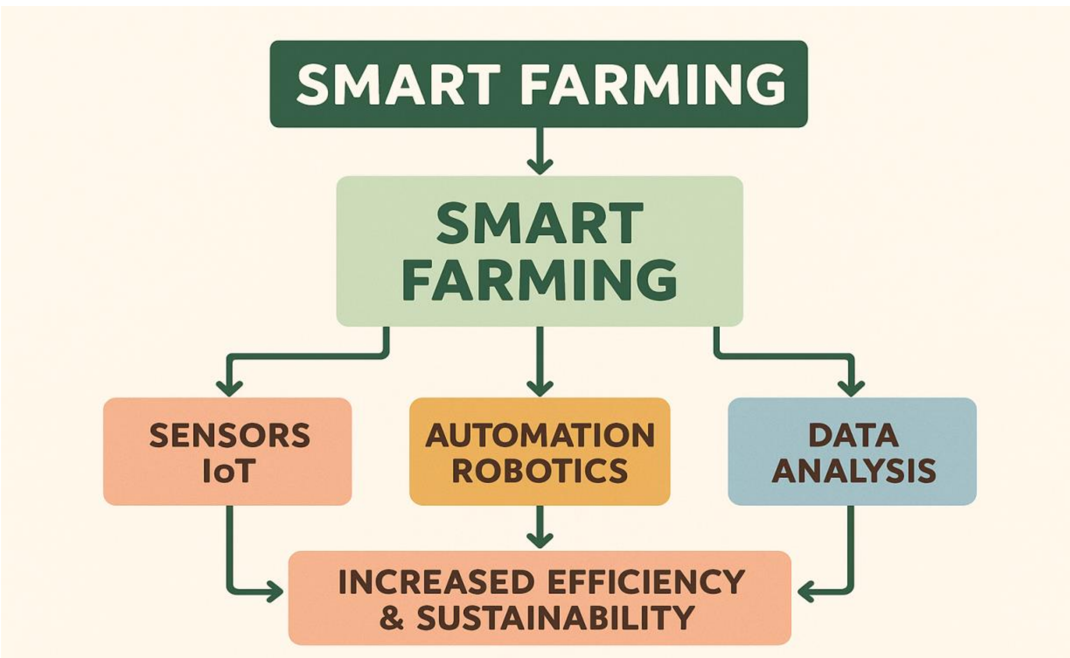

Fig. 1 Illustration showing the pictorial view of smart farming techniques

Core technologies in smart farming

Internet of Things (IoT)

It is a technology that enables various devices to communicate with each other, and share data, for the smart management of the farm. It has impacts across many different industries, including healthcare, agriculture and more (Dhanaraju et al., 2022). This technology shares real time data with the farmer, through cloud-based platforms and sensors which help in the water conservation, precise irrigation, fertilizer optimization, reduced pesticide uses and lower environmental footprint. (Friha et al., 2021). For example, smart irrigation systems can automatically adjust watering schedules to align with soil moisture levels, causing water use to be up to 50% less than conventional watering systems (Liu et al., 2020).

Artificial Intelligence (AI) and Machine Learning (ML)

AI helps different sectors for better efficiency and profitability in their work, including agriculture. In agriculture, AI is used to predict the pests and diseases, improve fertilizer timing, minimizes yield loss, best planting time support climate resilience farming and reduce unnecessary pesticides application by analyzing the data collected by sensors, drones, and satellites (Friha et al., 2021). For instance, AI can be used to identify issues that occur in wheat yields, allowing for early intervention and preventing yield loss (Kamilaris et al., 2018).

Drones and satellite imaging

Drones also called unmanned aerial vehicles (UAV), transform agriculture into data-driven and precise information. Drones use the camera to help farmers to monitor crop health, growth patterns, and soil conditions (Ranjan et al., 2024). Farm areas that need attention from farmers such as pest attacks and nutrient deficiency can be easily identified by using drones. Satellites use remote sensing technology to give vital information for a range of agricultural applications, such as production prediction and crop health evaluation (Sishodia et al., 2020). According to Zhang and Kovacs (2012), drone-based remote sensing can improve crop yield predictions and reduce input costs (Fig. 2). In addition to monitoring and surveillance, the use of the advanced image analysis provides the farmers information regarding early stress detection, targeted nutrient management, reduced chemical inputs, monitoring crop health and precise resource management. Furthermore, temporal analysis of satellite data allows the evaluation of the long-term performance of a crop and land use changes, resulting in more sustainable land management practices.

Robotics and automation

The introduction of robotics and automation has enhanced smart farming by increasing efficiency, reducing labor costs, and improving productivity. Robotics and automation contribute in sustainability in agriculture by doing tasks such as planting, weeding, harvesting, and sorting crops with high precision which will reduce the herbicides dependence, minimize the labour shortage, increase the input precision and lower environmental contamination. This machinery is more beneficial for the large-scale farms. In agricultural farms, automated weed management systems use robotic arms, computer vision, and machine learning technologies to detect and eradicate weeds (Sethia et al., 2020). For example, robotic weeders can identify and remove weeds without herbicides, promoting eco-friendly practices (Bechar & Vigneault, 2017) (Fig. 2).

Big data analytics

Precision farming has seen a revolution due to data analytics, which uses vast amounts of data gathered from several sources to improve operational effectiveness and decision-making. Precision farming success is based on efficient data management and collection. Farmers collect weather, soil and crop data from a variety of sources, such as weather stations, drones, satellite imaginary, and IoT devices and this data improves the decision making, reduces the resource wastage and increases resilience under climate variability (Raj et al., 2021). Big data also aids in predicting market trends, improving supply chain efficiency (Wolfert et al., 2017).

Decision Support Systems (DSS)

In the context of smart farming, Decision Support Systems (DSS) are gaining importance as an enabler for farmers to make well-informed and timely decisions through the integration of diverse datasets. These systems combine data from IoT sensors, satellite imagery, weather forecasts, and historical farm records to generate actionable insights for irrigation scheduling, fertilizer management, and pest control (Wolfert et al., 2017; Kamilaris et al., 2017). DSS platforms employ advanced algorithms and predictive modelling approaches to enhance resource-use efficiency while minimizing environmental risks (Raj et al., 2021). In regions experiencing climate variability, DSS serve as critical tools for risk mitigation by providing early warning signals and adaptive management strategies (Friha et al., 2021). The integration of DSS into farming systems improves precision, reduces uncertainty, and effectively bridges the gap between data acquisition and farm-level decision-making.

Experimental data on smart farming

Improving rice production through smart fertilization

Ghazali et al. (2020) conducted an experiment that compares the use of smart fertilization (VRT) with traditional approaches in rice yield over three consecutive growing seasons. Nine sampling plots were used to gather the ground-through data. A UAV with a DJI Phantom 3 Professional Multirotor type is used to take NDVI images. The generated SPAD and GAI maps are used by the fertilizer calculation program to provide maps of fertilization treatments that include data on fertilization rates depending on specific areas. The generated map will be sent to NOMAD, which will utilize it to establish a connection with the fertilizer spreader (a Bogballe M3 spreader equipped with a calibrator). The results of the trial showed that VRT fertilizer decreased fertilizer input in a total amount of nitrogen per hectare by 11.9% when compared to conventional fertilizer (Table 2). Furthermore, 50% of the labor required for fertilizer application is eliminated by using VRT. The comparison of conventional and variable rate fertilizer applications during the experiment is depicted in Fig. 3.

Improving wheat through smart practices

The main purpose of a two-year experiment at the Ayub Agriculture Research Institute in Faisalabad was to improve the efficiency of nitrogen use and regulate nitrogen fertilizer. The Normalized Difference Vegetation Index was used to compare farmer practices with sensor-based nitrogen applications. The experimental findings indicate a 12% increase in wheat grain and a 29% decrease in N fertilizer use as compared to farmer’s practices. When compared to farmer-based N applications, improvements in wheat grain also result in a 39% increase in nitrogen uptake efficiency and a 59% increase in nitrogen fertilizer productivity (Ahmed et al., 2024).

Smart irrigation for maize production

Bonfante et al. (2019) assessed the LCIS Decision Support System (DSS) for Irrigation Management for Maize in Mediterranean Regions in Italy. Weather, soil moisture, and crop data were connected to the system to determine optimal irrigation schedules. The study showed that irrigation using the DSS was able to sustain the productivity of maize plants while using less water than the traditional irrigation practices. The results underscore the promise of smart irrigation systems for more efficient water use and sustainable crop cultivation in the face of water scarcity.

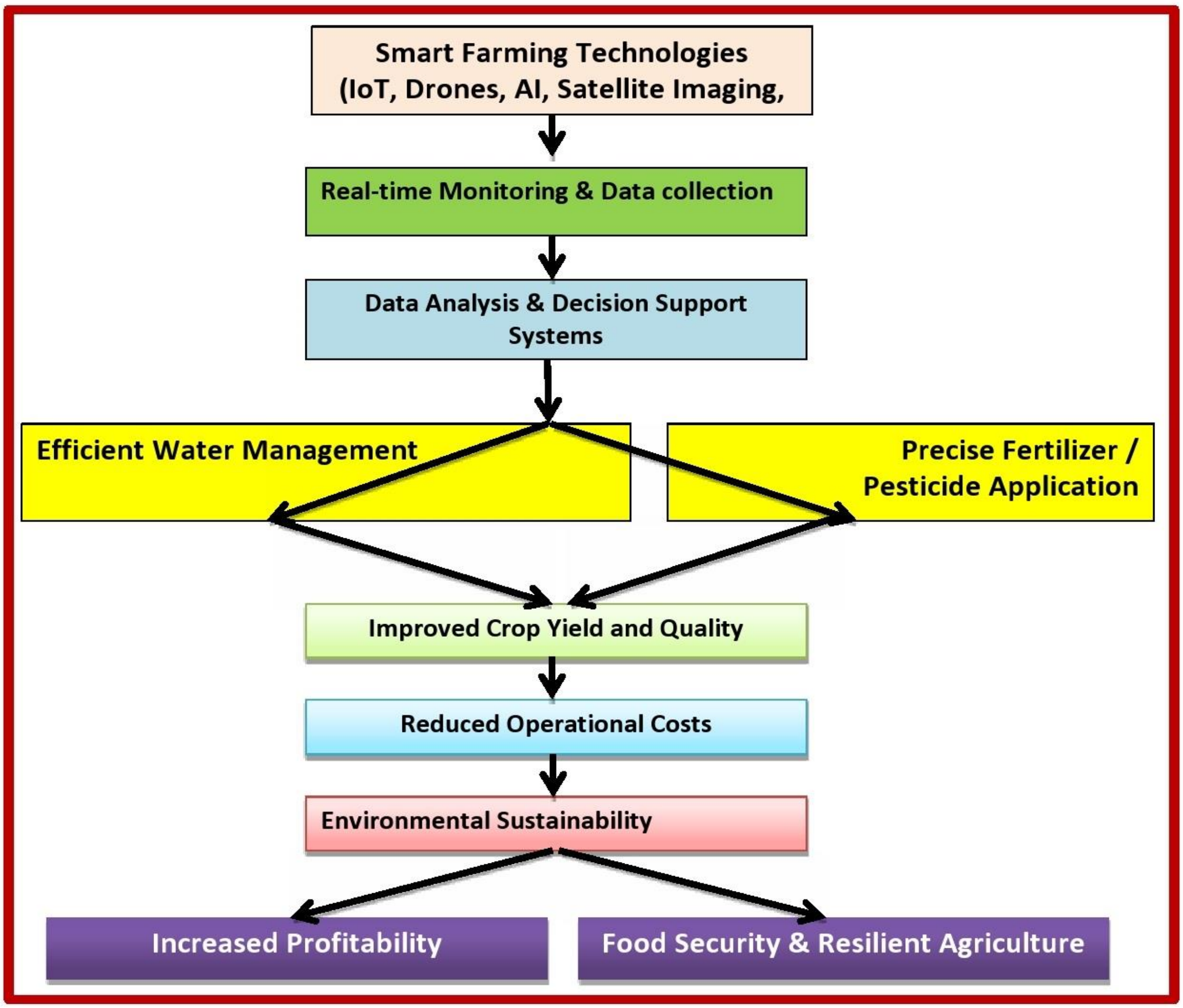

Fig. 2 Pictorial view describing the benefits of smart farming

Table 2 Comparison of inputs in variable rate technology (VRT) and conventional systems

Fertilizer application	Variable rate technology (VRT)	Conventional
Operation (ha/hr)	2.73	1.5
Field Variation (%)	5-10	22-30
Capacity (kg)	300-400	25
Spreading distance	14-16	8-10

UAV-based precision weed management

Allmendinger et al. (2024) assessed the potential of using high-resolution unmanned aerial vehicle (UAV) imagery for the spot spraying of herbicides in commercial maize fields in the southernmost region of Germany. Automated image classification was used to produce aerial weed maps to direct site-specific applications of herbicide in weed-infested areas. About 94% of weed plants were correctly identified, weed control efficacy was comparable to the conventional broadcast spraying (up to 86%) and herbicide use was reduced by 47% while maintaining maize yield. The results indicate that precision weed management using UAVs has the potential to significantly reduce chemical inputs with minimal loss in crop productivity, which is crucial for achieving sustainable agriculture.

Fig. 3. The graph shows the amount of N fertilizer saved by using VRT technology. Reduced amount of fertilizer was incorporated by using VRT technology which accounted to be 2.6% in season 1, 4.5% in season 2and 11.9% in season 3 as compared to conventional fertilizer rate application (adopted and modified after Ghazali et al. 2020).

Regenerative agriculture

It is an approach that aims to improve the soil health, enhance biodiversity, and help to combat climate change. RA promotes sustainable practices that not only conserve but enhance natural resources. Contrary to this, conventional agriculture commonly leads to soil erosion, nutrient depletion, and environmental damage but RA helps to ensure long-term productivity and environmental stability (Newton et al., 2020; Khangura et al., 2023). However, the fundamental principles of RA help to ensure the sustainability of resources for current and future generations but conventional agriculture exploit those resources and decrease the use efficiency (Newton et al., 2020; McGuire, 2018; Lal, 2020). Moreover, no-till farming, organic cropping, cover crops, crop rotation, integrated livestock management, and minimizing the use of synthetic inputs are some of the methods that are included in RA, which aims to achieve sustainability (Giller, 2021; Rehberger et al., 2023).

Principles of regenerative agriculture

The advantages of developing a "regenerative agriculture" are not just environmental, but climate change mitigation and adaptation. RA helps to sequester carbon in soil because of practices like cover cropping and reduced tillage, which build soil organic carbon, ultimately lowering the amount of carbon dioxide in the atmosphere. Better soil structure and water holding capacity also make for more resilient soils to droughts and extreme weather conditions, which are increasingly common in the new climate. What's more, the systems of regeneration encourage ecological equilibrium by encouraging the growth of useful microorganisms in the soil and improving nutrient circulation, thereby minimizing reliance on inorganic fertilizers and pesticides. The core principles of RA revolve around fostering a healthy ecosystem. These principles include:

Minimizing soil disturbance

Conventional agricultural practices disturb the natural structure of the soil causing erosion and loss of organic matter. Contrary to this, RA practices such as no-till or low-tillage practices enhance soil health and promote microbial activity crucial for nutrient cycling (Fig. 4).

Diversity of plant species

Biodiversity can be enhanced by incorporating a different crop in rotations or intercropping systems. This practice improves soil health, reduces pest and disease pressures, and enhances resilience to extreme weather conditions (Nichols et al., 2015).

Maintaining living roots in the soil

In regenerative agriculture, living plants are used as the cover crops which help to feed microorganisms. This practice improves carbon sequestration, improves water infiltration and prevents soil erosion (LaCanne and Lundgren, 2018). The use of living roots with the use of cover crops also plays a role in climate change mitigation by increasing the soil organic carbon. The average soil organic C stocks were 7.6% greater with cover crops than under no-cover crop fields, and cover crops also improved soil structure and biological activity according to a global meta-analysis (Poeplau & Don, 2015).

Integrating livestock

Incorporating livestock with a managed grazing practice mimics the natural ecosystem. Animals aid in the breakdown of plant matter, the distribution of nutrients through manure, and the promotion of plant development (Teague et al., 2016).

Using organic inputs and reducing chemicals

Regenerative farming prioritizes organic additives like compost and green manure above inorganic fertilizers and herbicides. As a result, pollution is decreased, and soil biology is improved.

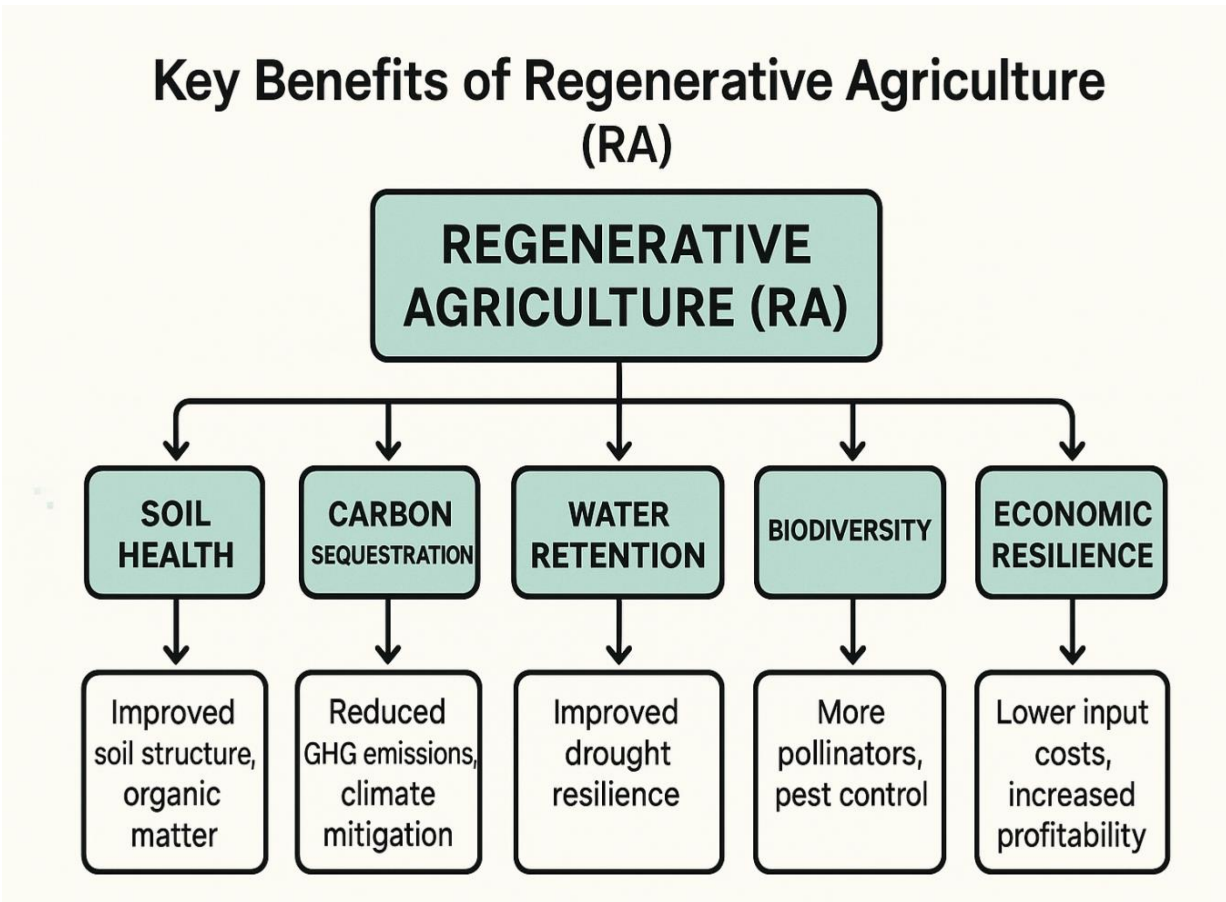

Fig. 4. Key benefits of Regenerative Agriculture (RA)

Applications of regenerative agriculture

Crop rotation and diversification

To enhance soil health, productivity, water uptake, and beneficial microbes, crop rotation entails growing various crops consecutively on the same piece of land (Fahad et al., 2021; He et al., 2021). Avoiding successive crops from the same family, switching between shallow and deep-rooted crops, replacing exhaustive crops with restorative ones, such as leguminous crops, and switching between short- and long-duration crops are all principles of crop rotation (Ball et al., 2005). The use of diversified crop rotations has been found to enhance crop productivity. A global meta-analysis showed that an increase in crop diversification boosted average yield by 14% and improved biodiversity and ecosystem services. An average increase in crop diversification of 14% was found to boost yields in a global meta-analysis while simultaneously improving biodiversity and ecosystem services (Beillouin et al., 2021).

Mulching

Mulching involves covering the soil with either organic or inorganic materials to conserve soil and water (El-Beltagi et al., 2022). It has several advantages, such as retaining moisture, controlling temperature, suppressing weeds, improving soil fertility, preventing erosion, and controlling diseases and pests (Khose et al., 2023; Kumar and Usadadiya, 2023). Properly mulching can significantly enhance soil moisture and control soil erosion. El-Beltagi et al. (2022) reported soil evaporation was decreased by 25-50%, soil moisture was increased by 10-30%, and soil erosion was decreased by up to 90% with different mulches and different climatic conditions.

Agroforestry

Agroforestry produces a range of goods, including timber, fuel, fiber, and food. Additionally, it increases agriculture productivity. In addition to preventing land degradation, agroforestry increases soil health, water capacity, and biodiversity on land (Khan et al., 2017; Singh et al., 2022; Castle et al., 2022). Overall, it helps to mitigate climate change and makes a substantial contribution towards environmentally friendly and sustainable agricultural practices. Carbon storage is another way in which agroforestry helps address climate change. A global synthesis estimated agroforestry systems sequester around 0.29-15.21 Mg C ha^{-1} yr^{-1} depending on climate, tree species and management (Nair et al., 2010).

Integrated crop-livestock system

As farming areas expand the rangeland is getting smaller. This issue can be resolved by implementing the Integrated Crop-Livestock System (ICLS), which employs animal excreta (poultry manure, farmyard manure) to improve soil health and productivity. This strategy might be the secret to attain both food security and environmental sustainability (Lemaire et al. 2013; Nikzad and Nusrathali, 2023). Long-term integrated crop-livestock systems have been shown to raise SOC by 20-30% over conventional cropping systems, but without increased use of fertilizer, and to enhance nutrient cycling (Lemaire et al., 2014).

Integration of smart farming and regenerative agriculture

Resource efficiency, higher agricultural yields, lower labor expenses, and environmental preservation are just a few benefits of smart farming (Wolfert et al., 2017). In the same way, RA offers several advantages, including increased yields, environmental preservation, biodiversity enhancement, lower input costs, and overall increased farm profitability (LaCanne & Lundgren, 2018). The most pressing issues facing the modern world are how to feed a population that is expanding quickly and how to lessen the effects of climate change (United Nations, 2022). RA and smart farming provide encouraging answers to these urgent problems. Research on these practices is still less reported, though, and there is a noticeable lack of studies examining how they might be integrated (Klerkx et al., 2019). The case studies on smart farming and RA are shown in Table 3. The concept of smart farming combined with regenerative agriculture could be visualized as a synergy between data driven technologies and ecological farming, that makes farming more efficient and scalable. For example, soil moisture and nutrient dynamics can be monitored in real-time using soil sensors, which can be connected to the IoT to enable precise implementation of regenerative practices like cover cropping and organic amendments. Similarly, AI can be used to enhance the optimization of crop rotations and biodiversity management, identifying patterns that can provide the greatest ecosystem services. This integration will enhance productivity and ensure more precision and flexibility in the application of regenerative practices in various agroecological situations. This change from an input-centric to knowledge-centric agriculture is a move towards more sustainable and resilient systems.

By integrating ecological sustainability with technological innovation, smart farming and RA offers a chance to tackle today's agricultural problems (Pretty & Bharucha, 2014). By utilizing automation, data-driven decision-making and real-time monitoring, smart farming technology can improve the effectiveness of regenerative methods (Ghosh et al., 2025). In agroforestry systems, for instance, drones can track biodiversity (Torres-Sánchez et al., 2015), and IoT-enabled sensors can optimize irrigation for cover crops. Farmers can improve output and restore ecological balance at the same time due to this integration. However, securing the cost and accessibility of technology as well as integrating these systems with various farming contexts present challenges (Eastwood et al., 2017). To ensure the effectiveness and scalability of this integration, cooperation between governments, researchers, and the corporate sector is crucial. Research on the integration of RA and smart farming must be given top priority. By combining these strategies, we may greatly lower the climate impact on agriculture while increasing agricultural productivity (Giller et al., 2021).

Challenges and future perspectives

The current challenges in the agriculture sector are to feed the growing population which is expected to rise to 10 billion in 2050. With the growing population, the area of agriculture kept decreasing due to the rise in construction work and soil degradation. Moreover, the emission of greenhouse gases is another burning issue that needs a critical solution. Therefore, it is a dire need to improve agricultural practices so we can increase our yield and mitigate climate change. Smart farming and RA techniques are the ultimate solutions to these challenges. Several researchers showed that both farming practices increase yield, overall profitability and cause less harm to the environment and conserve our resources. The adoption of this farming practice is hindered by high initial cost as it requires high investment initially for the installation of advanced technologies like IoT, drones and sensors. Furthermore, the initial decline in the crop yield also makes farmers resistant to adopt regenerative practices. Unavailability of infrastructure, knowledge gaps and integration complexity are the key challenges that farmers face while adopting these practices. The government should provide some subsidies for adopting a smart farming policy and build infrastructure that will facilitate farmers. Research institutions and universities should explore advancement in these practices and fill the knowledge gap by inaugurating seminars and other study-related programs for smart farming and RA. Another crucial aspect is the digital divide between developed and developing areas, restricting equal access to smart farming technologies. Unreliable internet connection, high costs of digital infrastructure and the lack of technical expertise in the agriculture sector are preventing the use of tools for precision agriculture in many low-income agriculture systems. Further, issues about data ownership, privacy and cybersecurity are becoming important in the digitalization of agriculture. The challenges must be met through collaborative work between governments, the private sector and research institutions, with the aim of creating affordable and easy-to-use technology and supportive regulations. Smart farming technologies and regenerative farming constitute a paradigm shift in today's agriculture. Both methods have been attempted separately, but combining the two approaches represents a complete answer to the two problems of food production and environmental sustainability. Further research is needed to create models specific to the location which combine the use of technological tools with ecological principles, and solutions that can be adapted to different farming systems and socio-economic conditions.

Table 3 Case studies on smart farming and regenerative agriculture

Location	Practice	Key findings	Benefits	References
Rice fields, Malaysia	Variable Rate Technology (VRT) for fertilization	Reduced nitrogen uses by 11.9%, saved 50% labor vs. conventional methods	Lower fertilizer runoff, improved resource efficiency	Ghazali et al. (2020)
Wheat fields, Pakistan	Sensor-based N application (NDVI monitoring)	12% higher yield, 29% less N fertilizer vs. farmer practices	Increased N-use efficiency, reduced GHG emissions	Ahmed et al. (2024)
U.S. farms	Regenerative practices (no-till, cover crops)	78% higher profits, 50% more soil organic matter vs. conventional farms	Enhanced carbon sequestration, biodiversity	LaCanne & Lundgren (2018)
Global (IoT case study)	Smart irrigation systems	50% water savings through soil moisture sensors	Mitigated water scarcity, reduced energy use	Liu et al. (2020)
North American rangelands	Integrated livestock grazing	30% higher soil carbon storage in managed grazing systems	Combats desertification, improves pasture resilience	Teague et al. (2016)

Conclusion

Implementing regenerative agriculture (RA) with the application of smart farming technologies offers an attractive approach to sustainable agriculture. This synergy helps solve major problems in the world like the degradation of resources, climate change and food scarcity. With regards to soil health and biodiversity, RA can be said to assist in restoring health whereas, with respect to precision and efficiency of resource utilization, smart farming can be said to assist with advanced technological aids. All these are viable strategies that can be implemented together in the development of resilient productive agriculture system to meet the increasing demand of food without compromising the environmental sustainability. But, for widespread adoption, there are major challenges to be faced, such as lack of infrastructure, knowledge and access to technology. Concerning investments of research, farmer education and policy frameworks must be made for this shift to be possible. All such endeavors will help to pave the way for an agricultural paradigm that is able to sustain human livelihoods and ecological integrity. The effective integration of smart farming and regenerative agriculture needs to happen in a coordinated way between policy makers, scientific research, industry and farming communities. Rural digital infrastructure, low-cost precision agriculture tools and farmer training are areas that governments should prioritize for farmer adoption support. Financial risks of transition could be diminished through a financial package of targeted incentives such as subsidies for precision equipment, carbon farming schemes and payments for ecosystem services. Open agricultural data, digitized extension services, and public-private partnerships will enhance knowledge transfer, particularly to smallholder farmers, through policy support. Integrated systems comprising artificial intelligence, Internet of Things, remote sensing, robotics and big data analysis coupled with regenerative practices in various agroecological conditions should be developed as research topics for the next 5–10 years. There is a need for long-term field trials to determine the impact of these treatments on yield, soil organic carbon, biodiversity, GHG emissions, water-use efficiency and farm profitability. Economic feasibility and scalability, as well as farmer acceptability, especially in the low-income areas, need to be explored in future. Moreover, there is a need for standardization of sustainability indicators and decision support tools to be able to assess smart-regenerative farming systems uniformly, both on a crop and a regional level.

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