Souvenir

National Seminar on Smart Technologies for Sustainable Agriculture and Environment

ICAR-Central Research Institute for Dryland Agriculture, Hyderabad
22-23 February 2024

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Organized by
Indian Society of Agrophysics, New Delhi
and
ICAR-CRIDA, Hyderabad

भाकृअनुप ICAR

CENTRAL RESEARCH INSTITUTE FOR DRYLAND AGRICULTURE 1985 केवाकृअनुसं

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अर्जुन मुंडा
Arjun Munda

आज़ादी का अमृत महोत्सव

सत्यमेव जयते

मंत्री
जनजातीय कार्य मंत्रालय एवं
कृषि एवं किसान कल्याण मंत्रालय
भारत सरकार

Minister
Ministry of Tribal Affairs and
Ministry of Agriculture &
Farmers Welfare
Government Of India

MESSAGE

I am happy that the National Seminar on 'Smart Technologies for Sustainable Agriculture and Environment' are jointly organizing by the Indian Society of Agrophysics and the Indian Council of Agricultural Research during 22–23 February 2024 at ICAR-CRIDA, Hyderabad. Seminar will have a special focus on the use of agrophysical technologies for smart agriculture and sustainable environment. The development of new crop varieties helps us to improve the yield potential of crops, however, it is only agrophysics that can assist to unleash the untapped potential. We should give simultaneous attention to use of modern technologies for management of natural resources. I hope the Seminar will show the way to achieve Goal 2 of the UN Sustainable Development decade viz., "End hunger, achieve food security and improved nutrition and promote sustainable agriculture".

On this occasion, best wishes to the organizers and participants.

(Arjun Munda)

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कृषि एवं किसान कल्याण मंत्रालय, कृषि भवन, नई दिल्ली–110 001

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सचिव (डेयर) एवं महानिदेशक (आईसीएआर)
Secretary (DARE) &
Director General (ICAR)

Message

I am happy to know that the Indian Society of Agrophysics and the Indian Council of Agricultural Research are organizing the National Seminar on ‘Smart Technologies for Sustainable Agriculture and Environment’ at ICAR-CRIDA, Hyderabad from 22–23 February, 2024. Impressive achievements have been made world over in better utilization of Natural Resources and enhancing agricultural production. However, the burgeoning demographic pressures, have posed a formidable challenge to the policy makers, scientists and all implementing agencies for providing livelihood to teeming millions.

The agricultural production system is a highly complex subject which encompasses various disciplines of agricultural sciences. The Agricultural Physicists have played a pivotal role in developing appropriate technologies in different agro-climatic conditions for increasing productivity. I hope that the delegates attending this Seminar will discuss and interact on issues related to the use of simulation modelling, biophysical techniques, remote sensing, drone technology, machine learning and AI for precise use of natural resources and also to come out with viable research and management strategies for providing food and nutritional security and employment to the masses.

I wish the Seminar a grand success.

(Himanshu Pathak)

20th February, 2024
New Delhi

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उप महानिदेशक (प्राकृतिक संसाधन प्रबंधन)
Dr. Suresh Kumar Chaudhari
Deputy Director General (Natural Resources Management)

15.02.2024

Message

I am genuinely pleased to learn about the National Seminar on 'Smart Technologies for Sustainable Agriculture and Environment' taking place at ICAR-CRIDA, Hyderabad from 22–23 February 2024. As someone who has closely observed the remarkable progress of Indian agriculture since independence, I recognize the pivotal role that agrophysical practices have played alongside the introduction of seeds and subsequent green revolution. These practices, tailored to various agro-environments, have been developed over the years by dedicated agricultural scientists. However, the demands of modern intensive agriculture necessitate cautious and pragmatic approaches to ensure environmental safety and sustainable food production. It is imperative to evolve multi-pronged strategies that incorporate various facets of modern agriculture to address second-generation issues concerning soils, water, and the environment. I firmly believe that Indian agriculture possesses the potential and adaptability to surmount these daunting challenges with the support of resilient and committed agricultural researchers.

In this context, the chosen theme of the Seminar, 'Smart Technologies for Sustainable Agriculture and Environment', is both fitting and timely. I anticipate that the discussions and deliberations during the Seminar will prove immensely valuable and contribute to resolving the multifaceted challenges associated with agriculture, livelihoods, and global environmental security.

I wish the Seminar a grand success.

(S.K. Chaudhari)

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(A DEEMED TO BE UNIVERSITY UNDER SECTION 3 OF UGC ACT, 1956)

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MESSAGE

I am indeed happy to learn that the Indian Society of Agrophysics and the Indian Council of Agricultural Research have taken the initiative to organize a National Seminar on the 'Smart Technologies for Sustainable Agriculture and Environment' at ICAR-CRIDA, Hyderabad from 22–23 February 2024. I have been closely watching the application of Agrophysics in Indian agriculture. The advent of wonder seeds and the subsequent green revolution would not have been that spectacular without matching agrophysics research under different agro-environments. Agrophysics has made significant progress in research, teaching, and training in the subject areas of Soil Physics, Agricultural Meteorology, Biophysics, Remote Sensing, GIS, and new areas of research like precision agriculture, thermal imaging, application of drone technology in agriculture, big data analysis, etc. In addition, Agrophysics is also catering to the needs of the farmers of the NCR, Delhi, through the weather-based agromet advisory services. It has made significant contributions in developing web-based applications like crop models, decision support systems for soil, crop and pest management, soil physical health assessment, satellite-based crop condition monitoring etc. However, present-day intensive agriculture demands a more cautious and pragmatic approach in order to ensure environmental safety and sustainable food production. Multi-pronged approaches involving various components of modern-day agriculture need to be evolved to tackle second-generation problems of soils, water and the environment. I firmly believe that Agrophysics can play a pivotal role in achieving the goal of smart agriculture with the help of IoT, Drone Technology, Remote Sensing, GIS, Sensors, and AI-based soil health assessment. I congratulate the organizers for choosing the most appropriate theme of the Seminar. I am sure that the discussions and deliberations during the Seminar would be of great benefit to the scientific community in resolving the problems associated with agriculture, livelihood, smart agriculture, and environmental safety.

I wish the Seminar a great success.

(Ashok Kumar Singh)

Indian Society of Agrophysics

Division of Agricultural Physics
ICAR-Indian Agricultural Research Institute
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Dr Y S Shivay
President

MESSAGE

I am happy to know that the Indian Society of Agrophysics and the Indian Council of Agricultural Research are organizing the National Seminar on the topical theme of 'Smart Technologies for Sustainable Agriculture and Environment'. Impressive achievements have been made the world over in the cautious use of natural resources management and enhancing agricultural production. However, the burgeoning demographic pressures, have posed a formidable challenge to the policymakers, scientists, and all other stakeholders including implementing agencies for providing livelihood to teeming millions.

The agricultural production system is a highly complex subject which encompasses various disciplines of agricultural sciences. The Agrophysicists have played a pivotal role in addressing the complex soil-plant-atmosphere continuum and developing appropriate technologies for different agro-climatic conditions. I hope that the delegates attending this Seminar will discuss and interact on pertinent issues related to smart agriculture, climate change, and management of resources to come out with viable research and development of resource-efficient strategies for providing food and nutritional security, also employment opportunities to the masses and doubling farmers' income.

I wish the National Seminar a grand success in its endeavours.

(Y S Shivay)

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डॉ. विनोद कुमार सिंह
निदेशक
Dr. Vinod Kumar Singh
Director

MESSAGE

I am happy to know that the Indian Society of Agrophysics and the Indian Council of Agricultural Research are organizing National Seminar on 'Smart Technologies for Sustainable Agriculture and Environment' at ICAR-CRIDA, Hyderabad from 22–23 February, 2024. Impressive achievements have been made world over in natural resources management, enhancing agricultural production. However, the burgeoning demographic pressures, have posed a formidable challenge to the policy makers, scientists and all implementing agencies for providing livelihood to teeming millions.

The agricultural production system is a highly complex subject which encompasses various disciplines of agricultural sciences. The Agrophysicists have played a pivotal role in developing appropriate technologies for different agro-climatic conditions. I hope that the delegates attending this Seminar will discuss and interact on issues related to smart agriculture, climate change and management of all our resources to come out with viable research and development strategies for providing food and nutritional security and employment to the masses.

I wish the Seminar all success in its endeavours.

(Vinod Kumar Singh)

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National Seminar on Smart Technologies for Sustainable Agriculture and Environment
22-23 February 2024, ICAR-CRIDA, Hyderabad

Current Initiatives under Smart Agriculture in India

S.K. Chaudhari[1]*, Pragati Pramanik Maity[2] and Abhradip Sarkar[2]

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Agriculture is one of the most important sectors of the Indian economy, providing livelihood to more than half of the population and contributing to about 18% of the GDP. However, the sector faces many challenges such as low productivity, climate change, water scarcity, soil degradation, market inefficiencies, and post-harvest losses. To overcome these challenges and enhance the sustainability and profitability of agriculture, there is a need to adopt smart technologies that can improve the efficiency and effectiveness of various agricultural operations and processes. Smart technologies are those that use information and communication technologies (ICT), artificial intelligence (AI), internet of things (IoT), big data analytics, cloud computing, blockchain, drones, sensors, robotics, and biotechnology to collect, process, and disseminate relevant and timely information and services to farmers and other stakeholders.

The agriculture sector is crucial for India's economic growth. Agriculture contributed to nearly 17.8% of India's Gross Value Added (GVA) in 2019–20. The development indicator collection maintained by the World Bank shows that in 2020, 41.5% of Indians work in the agriculture sector. Agriculture is an important sector from a socio-economic perspective, which needs attention and awareness at all levels (Thomas, 2023). The agriculture sector has faced many problems in the recent years, such as low yields, soil erosion, water scarcity, increased oilseed imports, malnutrition, unstable prices, poor infrastructure linkages, post-harvest loss, and lack of information. However, negative climate changes are still one of the biggest challenges for this sector. India lost about 5.04 million hectares of crop area because of cyclones, floods, cloudbursts, and landslides until November 25, 2021. These disasters have badly affected farmers, especially small farmers who make up almost 85% of the total farmers in India (Down to earth news). Therefore, smart agriculture is urgently needed in India. The Indian government has taken many steps for improving the sector, keeping in mind its importance. The government is also looking for ways to increase agricultural productivity and income of farmers.

Smart Agriculture in India

Smart farming is very important for the Indian agriculture sector. Smart farming, which uses sensors and automated irrigation systems, can help check agricultural land, temperature and soil moisture (Mohamed *et al.*, 2021). This would let farmers watch crops from anywhere. Also, smart farming can help connect digital and physical infrastructures which would help small farmers. The small and poor farmers of India have trouble connecting digital and physical infrastructures which affects their income growth. Agro-based start-ups can help the farmers and give them such good and cheap solutions. A report by the National Association of Software and Services Companies (NASSCOM) in 2019 said that there were more than 450 agri-based tech driven start-ups in India in

2019. This number has gone up a lot in the last two years as the sector got more investments and money. Agri-based tech-driven start-ups have been very creative in helping farmers and changing farming methods. They have also solved one of the biggest problems (climate change) through climate-smart farming (Beniwal and Mathur, 2023).

Climate-smart Agriculture

The growing population and changing diets have put a lot of pressure on land in India. Farmers are finding it hard to keep up as crop yields stop growing, soil quality goes down, water becomes scarce, biodiversity reduces, and natural disasters happen more often. Also, agriculture makes up almost 14% of India's total greenhouse gas emissions. Climate-smart agriculture (CSA) can help change agri-food systems in a good way and lessen the bad effects of climate changes while making food and energy in a sustainable way. Farmers in India are slowly seeing the benefits of CSA. CSA is a way of managing cropland, livestock, forest, and fisheries together. CSA also deals with the linked problems of food security and fast climate change (Hussain *et al*., 2022). CSA can fulfil the objectives of

a) **More productivity:** CSA can help in making more food without losing the quality which would improve nutrition security and increase income among farmers, especially the poor and weak groups.

b) **Better resilience:** CSA can lower the risk of pests, drought diseases and climate-related shocks and dangers. It can also help farmers improve and grow the long damaged and bad environment.

c) **Less emissions:** One of the main benefits of CSA is expected to be emission reduction. Automation makes less work for people which would help lower emissions per calorie of food made, stop cutting down trees, and lower emission of greenhouse gases like carbon dioxide into the air. This will lead to less use of human power from sources that harm the environment. India is slowly using climate-smart ways of farming which will help to improve the environment of India and lower greenhouses gases from agriculture practices. For example, the farmers of Dhundi village in Gujarat have started using clean energy sources like solar power for irrigation. The solar power programme helps farmers in two ways: under the programme, farmers give electricity to the local grid; for this, they get rewards. Smart farming allows crop variety which helps farmers depend less on monsoon for water (Bhatt *et al*., 2019).

Budget of India in the year 2022 aims at smart and modern farming methods. The Prime Minister of India said that agricultural loans have increased 2.5 times in the last seven years. These loans will help improve agriculture a lot and boost natural farming, with a main focus on Agri-waste management. Also, under the PM Kisan Samman Nidhi scheme, US$ 26.4 billion (Rs. 2,00,000 crore) has been given to 11 crore farmers. The government's work towards encouraging the use of organic products have made the organic products market grow to US$ 1.5 billion (Rs. 11,000 crore). The government is also giving money to Agri-tech startups and pushing the use of AI to change agricultural and farming ways.

Some of the recent smart technologies in agriculture in India are:

Smart irrigation: This technology uses sensors, weather data, and crop models to monitor and control the water supply to the crops, based on their water requirements and soil moisture levels (El-Naggar *et al*., 2020). This helps to save water, reduce wastage, and optimize crop growth and yield. Some examples of smart irrigation systems in India are Kisan Raja, Jain Irrigation, and FlyBird Farm Innovations.

The main methods of traditional methods are basin, furrow irrigations, strip irrigations, and basin irrigation and they are not made with an aim to conserve resources. The cost of the traditional irrigation system is very high. The improved traditional irrigation system with the use of modern technologies is called the modern irrigation system. The modern irrigation system has three types such as sprinkler irrigation system, pot irrigation system and drip irrigation system, etc. (Janani and Jebakumar, 2019). The modern irrigation system also has different other uses. Based on weather evapotranspiration controller-based, it is divided into the signal-based controller, Historic controller, and On-site weather measurement controller's irrigation system, etc. Based on the soil moisture sensor controller, it is divided into Suspended cycle irrigation systems and water on-demand irrigation. Those are some of the main divisions based on the use of components and properties. There are different sensors for controlling and sensing of modern smart technologies. The smart irrigation system has soil management and water management. Soil management uses different parameters such as soil moisture, soil temperature, soil conditions and soil dryness, etc. The water management uses different parameters such as dew point temperature, Evapotranspiration, air temperature, wind temperature, and humidity. Besides those parameters, the accuracy of prediction, rate of data transfer, effective usage are the other parameters to think about in the smart irrigation model (Blessy, 2021). Some examples of smart irrigation systems in India are:

KisanRaja: A smart irrigation device that helps farmers control their water pumps using a mobile phone or a landline phone. The device also provides voice alerts for power issues, water levels, and theft attempts (Narula, 2017).

CropX: A smart irrigation platform that uses wireless soil sensors and cloud-based analytics to provide real-time irrigation recommendations to farmers. The platform also integrates with weather data and satellite imagery to optimize irrigation scheduling (Balkrishna *et al*., 2021).

HydroPoint: A smart water management solution that uses IoT, AI, and big data to automate and optimize irrigation for landscapes, farms, and greenhouses. The solution also helps reduce water wastage, runoff, and pollution (Bwambale *et al*., 2022).

SunCulture: A smart irrigation solution that uses solar-powered pumps and drip irrigation systems to provide water and fertilizer to crops. The solution also offers a mobile app that helps farmers monitor and manage their irrigation remotely (Fairley, 2021).

Government Initiative

Pradhan Mantri Krishi Sinchai Yojana (PMKSY): This scheme aims to improve farm productivity and ensure better utilization of resources such as water through the implementation of efficient irrigation technologies. The Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) with the very important component of Per Drop More Crop (PDMC) – Micro Irrigation, is being implemented by the Ministry of Agriculture & Farmers Welfare - Department of Agriculture, Cooperation and Farmers Welfare, Government of India, since 2015- 16. India is increasingly facing acute water scarcity and the PDMC component focuses on improving water use efficiency at the farm level through promotion and support of Precision or Micro Irrigation (MI) which includes Drip and Sprinkler Irrigation. The main premise of the PDMC component is that the water use efficiency in India's agriculture is very low compared to global standards, and is reported to be as low as 25-35 percent, Vaidyanathan and Sivasubramaniyan (2004) – which indicates that 65 to 75 percent of the water is being wasted. This is substantially due to the widespread practice of conventional flood irrigation technique all over India. MI techniques can bring numerous benefits including not only enhanced water use efficiency, but also increase in irrigated area with the given quantity of water, enhanced crop productivity/ yields, labour cost savings, electricity and energy savings through lesser pumping hours. Under the government schemes described above, most of the states are giving subsidies of often over 70 percent for the installation of MI system, and the states often compete with each other to increase the subsidy component. There is a great need to better understand MI implementation, including the adoption of MI across crops, farmers and regions, the costs and benefits, and the impact of the technology on farmers, resources and agriculture, which would be very important for improving the implementation and benefits from the schemes (Roy and Majumder, 2020).

Smart farming: This technology uses AI, IoT, drones, and robotics to automate and optimize various farming activities such as sowing, weeding, harvesting, spraying, and grading. This helps to reduce labor costs, increase productivity, and improve quality and safety. Some examples of smart farming solutions in India are CropIn, Fasal, TartanSense, and AgNext.

Drones are uncrewed aerial vehicles that can be used for various purposes in agriculture, such as crop monitoring, irrigation, spraying, and mapping. Drones can help farmers improve their efficiency, productivity, and profitability by providing them with timely and accurate information and services (Rahman *et al*., 2021). Some of the benefits of using drones in agriculture are:

- Drones can help farmers assess the health and growth of their crops, detect pests and diseases, and identify nutrient and water deficiencies. This can help farmers take corrective actions and optimize their crop yields and quality (Pathak *et al*., 2020).
- Drones can help farmers save water and reduce chemical use by applying precise amounts of water and fertilizers to the crops, based on their needs and soil conditions. This can help farmers reduce their costs and environmental impact (Dutta and Goswami, 2020).
- Drones can help farmers collect and analyze high-resolution spatial data, such as soil maps, elevation maps, and crop maps. This can help farmers plan their crop rotation, irrigation, and harvesting strategies, and improve their land use efficiency (Gillan *et al*., 2021).
- Drones can help farmers connect with markets and buyers, by providing them with traceability and certification of their produce. This can help farmers increase their income and access to new opportunities (Sahoo *et al*., 2023).

According to a report by FICCI-EY, the drone market size in India will reach $885.7 million by 2021, with agriculture being one of the major sectors driving the demand. The Indian government is also supporting the use of drones in agriculture, by introducing policies and schemes such as the National Drone Policy, the Drone Rules 2021, and the Kisan Drone Scheme2. These initiatives aim to make it easier and cheaper for farmers and agri-tech startups to own and operate drones in the country (Edulakanti and Ganguly, 2023). Some of the leading drone companies and startups in India that are providing solutions for the agriculture sector are Aarav Unmanned Systems, Skylark Drones, SenseHawk, and SunCulture.

Smart advisory: This technology uses big data analytics, cloud computing, and mobile applications to provide personalized and timely advice and recommendations to farmers on various aspects of crop management such as crop selection, pest and disease control, fertilizer and pesticide application, and market linkages. This helps to increase crop productivity, profitability, and resilience. Some examples of smart advisory platforms in India are AgroStar, DeHaat, Gramophone, and KrishiHub.In India, advisories about weather and disease forecasts, markets and other information are sent by SMS or voice message alerts by agencies such as the farm science centers (Krishi Vigyan Kendras) (Saravanan, 2010; Das *et al*., 2016), IFFCO Kissan Sanchar Limited (IKSL) and ReutersMarket Light (USAID, 2000; Fafchamps and Minten, 2012).

AgroStar: A mobile app that connects farmers with agronomists, experts, and dealers, and provides crop-specific solutions, weather updates, and quality inputs.

DeHaat: A platform that offers end-to-end agricultural services to farmers, such as crop advisory, input delivery, crop monitoring, credit, insurance, and market access.

Gramophone: A platform that leverages AI and big data to provide personalized crop recommendations, soil health analysis, pest and disease diagnosis, and market insights to farmers.

KrishiHub: A platform that uses AI and IoT to provide crop planning, weather forecasting, pest and disease detection, and crop health monitoring to farmers, and also connects them with buyers and retailers.

Smart disease detection: Smart disease detection of plant in India is a technology that uses AI and computer vision to identify and diagnose plant diseases using images captured by drones or cameras. This technology can help farmers prevent crop losses, improve crop quality, and reduce the use of pesticides. Some of the methods and applications of smart disease detection of plant in India are:

Deep learning: This is a technique that uses neural networks to learn from large amounts of data and perform complex tasks such as image recognition, classification, and segmentation. Deep learning can help detect plant diseases with high accuracy and speed, by analyzing the color, shape, texture, and pattern of the plant leaves and stems. Some examples of deep learning models used for plant disease detection are convolutional neural networks (CNNs), recurrent neural networks (RNNs), and generative adversarial networks (GANs) (Nerkar and Talbar, 2021).

IoT and cloud computing: This is a technique that uses internet-connected devices and cloud-based platforms to collect, store, process, and share data and services. IoT and cloud computing can help enable real-time and remote monitoring and diagnosis of plant diseases, by transmitting the images captured by drones or cameras to the cloud servers, where the deep learning models can analyze them and provide feedback and recommendations to the farmers (Suneja *et al.*, 2022). Some examples of IoT and cloud-based platforms used for plant disease detection are Losant, MQTT, and Raspberry Pi.

Smart disease detection of plants in India is a vital aspect of modern agriculture aimed at ensuring timely identification and management of plant diseases to mitigate crop losses and enhance agricultural productivity. Leveraging advanced technologies such as artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT), India is increasingly adopting smart disease detection methods to monitor, diagnose, and treat plant diseases effectively. One prominent approach involves the use of sensors and imaging techniques to detect subtle changes in plant physiology and morphology indicative of disease presence. These sensors can capture data on various parameters such as leaf color, temperature, humidity, and spectral reflectance, which are then analyzed using AI and ML algorithms to identify patterns associated with specific diseases. Additionally, IoT-enabled devices facilitate real-time monitoring of environmental conditions in agricultural fields, allowing farmers to detect disease outbreaks early and take prompt preventive measures. This proactive approach minimizes the spread of diseases and reduces the need for indiscriminate use of chemical pesticides, thereby promoting sustainable agriculture. Furthermore, mobile applications and decision support systems provide farmers with accessible tools for disease diagnosis, symptom recognition, and recommended management practices. These digital solutions empower farmers with knowledge and actionable insights, enabling them to make informed decisions and adopt appropriate disease control strategies. Overall, the implementation of smart disease detection technologies in Indian agriculture holds tremendous potential to revolutionize disease management practices, improve crop health, and contribute to food security and sustainable development. By harnessing the power of innovation and technology, India is poised to enhance its resilience against plant diseases and bolster agricultural productivity for the benefit of farmers and society as a whole (Kose *et al*., 2022).

Conclusions

The integration of smart technologies in agriculture marks a transformative shift towards sustainable and efficient farming practices in India. With the adoption of innovative solutions such as precision agriculture, Internet of Things (IoT) devices, artificial intelligence (AI), and remote sensing technologies, Indian farmers are empowered to make data-driven decisions, optimize resource usage, and enhance crop yields. These smart technologies facilitate real-time monitoring of environmental conditions, soil health, and crop performance, enabling farmers to detect issues such as water stress, nutrient deficiencies, and pest infestations early on. By leveraging predictive analytics and machine learning algorithms, farmers can anticipate challenges and implement timely interventions, thereby minimizing crop losses and maximizing productivity. Furthermore, smart technologies foster inclusive growth by bridging the digital divide and providing smallholder farmers with access to valuable information and market linkages through mobile applications and digital platforms. This democratization of agricultural knowledge empowers farmers of all scales to improve their livelihoods and contribute to food security. Moreover, the adoption of smart technologies in agriculture aligns with India's commitment to sustainability and environmental stewardship. By promoting precision irrigation, organic farming, and integrated pest management practices, smart agriculture mitigates the adverse impacts of climate change, reduces dependence on chemical inputs, and fosters biodiversity conservation. As India continues to embrace the digital revolution in agriculture, there is immense potential for smart technologies to drive inclusive growth, enhance resilience to climate change, and ensure the long-term sustainability of the agricultural sector. Through collaborative efforts between government, industry, and farmers, smart agriculture will play a pivotal role in realizing India's vision of doubling farmer incomes and transforming the agrarian landscape for generations to come.

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India's Preparedness Towards Tackling Climate Change

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Climate change is one of the most critical global challenges of our times. Climate change impacts will range from affecting agriculture, further endangering food security to sea level rise and the accelerated erosion of coastal zones, increasing intensity of natural disasters, species extinction, and the spread of vector-borne diseases. Climate change is a global collective action problem and requires international cooperation for its solution. India is a party to the United Nations Framework Convention on Climate Change (UNFCCC), and its Kyoto Protocol (KP), and the Paris Agreement (PA). India is also a party to the Convention on Biological Diversity (CBD) and United Nations Convention to Combat Desertification (UNCCD).

India's agricultural production and productivity is being impacted by climate change. Changes in precipitation due to erratic monsoon patterns resulting in water scarcity or floods, rising temperatures leading to extreme heat stress, affecting crop development and yields. Climate change can create a more favorable environment for the proliferation of pests and diseases, affecting crop health and productivity. It also led to shifts in the timing of seasons, affecting the sowing and harvesting period of crops and disrupting the traditional agricultural calendars and practices. The production of major food crops like rice, wheat, maize, groundnut, soybean and many pulse crops in the country was affected in the drought years (2002-03, 2004-05, 2009-10 and 2014-15). Similarly, severe floods also affected several field and horticultural crops. Flooding for 24 hours severely affected tomato crop during the flowering stage. Onion during the bulb stage is highly sensitive to flooding. Severe heat wave in north and central India during March-May, 2022 affected the yield of wheat and other horticultural crops. According to the India Meteorological Department (IMD), India faced its hottest February in 2023. High temperature during the flowering and maturity led to loss in yield. A delayed monsoon delayed the sowing of the *kharif* crop in 2023 due to El nino effect.

As part of its 3rd National Communication, the Ministry of Environment, Forest and Climate Change (MoEFCC) conducted studies on impact of climate change in India. Climate change scenarios were analysed using high-resolution regional climate model. Simulations for 2020s, 2050s and 2080s indicate an all-round warming for the Indian subcontinent. Impact of climate change and climate variability on the water resources are likely to affect irrigated agriculture, installed power capacity, environmental flows in the dry season and wet season. Under the NAPCC missions, a number of R&D projects have been supported in climate change studies across India to assess the impact of climate change on coastal vulnerability, health, agriculture and water.

The climate change impact assessment was carried out in different parts of the country by ICAR using crop simulation models by incorporating the projected climates of 2050 & 2080. In absence of adoption of adaptation measures, rainfed rice yields in India are projected to reduce by 20% in 2050 and 47% in 2080 scenarios while, irrigated rice yields are projected to reduce by 3.5% in 2050 and 5% in 2080 scenarios. Climate change is projected to reduce wheat yield by 19.3% in 2050 and 40%

in 2080 scenarios towards the end of the century with significant spatial and temporal variations. Climate change is projected to reduce the *kharif* maize yields by 18 and 23% in 2050 and 2080 scenarios, respectively. *Kharif* groundnut yields are projected to be increased by 7% in 2050 scenario whereas in 2080 scenario the yield is likely to decline by 5%. It is also found that future climate scenarios are likely to benefit chickpea with increase in productivity. Projected effects of climate change on rainfed sorghum is reduction of yield by 8% in 2050 scenario. Climate change is projected to impact mustard negatively with seed yields reduction up to 7.9% in 2050 and up to 15% in 2080 scenarios. Soybean yields are projected to increase by 8% in 2030 and 13% in 2080 scenarios.

The Government of India has formulated various schemes that aid in preparedness of the country for increased agricultural production in the country for future changing climate. National Action Plan on Climate Change (NAPCC) was launched by the Indian government on 30th June 2008, which comprises eight National Missions that focus on specific areas of solar energy, energy efficiency, water, sustainable agriculture, health, Himalayan ecosystem, sustainable habitat, Green India, and Strategic knowledge for climate change. NAPCC promotes understanding of climate change, adaptation and mitigation, energy efficiency and natural resource conservation. Thirty-four States /Union Territories (UTs) have prepared their State Action Plans on Climate Change (SAPCC) in line with NAPCC considering the state specific issues relating to climate change. India has also proactively taken a lead in promoting international collaborations through International Solar Alliance and Coalition for Disaster Resilient Infrastructure and has undertaken various programmes and activities through these arrangements. Under the terms of the Paris Agreement, India has submitted its updated Nationally Determined Contributions (NDCs) on 26th August 2022 and submitted its long-term low carbon development strategy on 14th November 2022.

The Department of Science & Technology (DST) is coordinating and implementing two national missions, National Mission for Sustaining the Himalayan Ecosystem and National Mission on Strategic Knowledge for Climate Change (NMSKCC), as a part of the NAPCC. Under both missions a large number of R&D projects have been supported in climate change studies to assess the impact of climate change on sectors like Health, agriculture and water and to come up with coping adaptation strategies.

The National Mission for Sustainable Agriculture (NMSA) is one of the eight missions within the NAPCC, which aims at evolving and implementing strategies to make Indian agriculture more resilient to the changing climate. It has three major components *i.e.,* Rainfed Area Development (RAD), On Farm Water Management (OFWM) and Soil Health Management (SHM). Subsequently, four new programmes were introduced under the ambit of NMSA namely Soil Health Card (SHC), Paramparagat Krishi Vikas Yojana (PKVY), Mission Organic Value Chain Development in North Eastern Region (MOVCDNER) and Sub Mission on Agroforestry (SMAF). During 2015-16, Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) was operationalized wherein the OFWM component of NMSA was subsumed under Per Drop More Crop (PDMC) component of PMKSY. Additionally, the restructured National Bamboo Mission (NBM) was also launched in April 2018 under the ambit of NMSA. All these schemes enable to promote sustainable and resilient agricultural practices.

To meet the challenges of sustaining domestic food production in the face of changing climate, Indian Council of Agricultural Research (ICAR), Ministry of Agriculture and Farmers Welfare, Government of India launched a flagship network project namely National Innovations in Climate Resilient Agriculture (NICRA) in 2011. The project aims to develop and promote climate resilient agriculture to address vulnerable areas of the country and help the districts and regions to cope up with extreme weather conditions like droughts, floods, frost, heat waves, etc. The project has three components *viz.,* strategic research, technology demonstration and capacity building. The main thrust areas covered are (i) identification of the most vulnerable districts/regions, (ii) development of crop varieties and management practices for adaptation and mitigation and (iii) assessment of climate change impacts on livestock, fisheries and poultry vis-a-vis identification of adaptation strategies.

The NICRA project is implemented across the country in 151 climatically vulnerable districts. It assessed risk and vulnerability of 573 out of 650 predominantly agriculture districts as per Intergovernmental Panel on Climate Change (IPCC) protocol. A total of 109 districts are categorized as 'very high' and 201 districts as 'highly' vulnerable. Adaptation efforts have been underway in 151 out of these 310 (109 + 201) districts through NICRA. Efforts are now underway for conducting risk assessment at sub-district (block) level for the states of Odisha and Maharashtra. District Agriculture Contingency Plans (DACP) were prepared for 650 districts recommending location specific climate resilient crops and varieties and management practices for use by the state departments of agriculture and farmers. These agricultural contingency plans cover weather aberrations like drought (early, mid and late-season droughts), floods, unseasonal rains and extreme weather events such as heat wave, cold wave, frost, hailstorm, cyclone etc. This activity by ICAR in collaboration with State Agriculture Departments will enable preparedness to deal with drought and other weather aberrations.

Some of the most significant research initiatives under NICRA to address the climate change concerns are climate resilient technologies *viz.,* resilient varieties, resilient intercropping systems, conservation agriculture, crop diversification from paddy to other alternate crops like pulses, oilseeds, agroforestry systems, zero till drill sowing of wheat to escape terminal heat stress, alternate methods of rice cultivation (system of rice intensification, aerobic rice, direct seeded rice), green manuring, integrated farming systems, integrated nutrient management, integrated pest management, organic farming, site specific nutrient management, *in-situ* moisture conservation, protective irrigation from harvested rainwater in farm pond, micro irrigation method (drip and sprinkler) etc., have been developed and demonstrated to large number of farmers. Climate resilient varieties have been developed for crops *viz.,* rice, wheat, mungbean, lentil, maize and tomato that are resistant to extreme weather conditions and diseases. These varieties have been introduced in drought and heat wave affected districts, well adopted by farmers resulting in increased crop yields and monetary returns at different locations.

NICRA developed several doable rainfed technologies like rainwater management, efficient and profitable cropping systems, nutrient management, energy management, alternate land use/farming systems which can increase production, decrease cost of cultivation, reduce drudgery and enable farmers to complete farm operations timely. Simulation modelling studies indicate that adopting improved varieties coupled with improved agronomic management practices can minimize the yield loss due to extreme weather events in several crops. Planting methods such as zero till, raised bed planting, cropping intensification with harvested rain water demonstrated in North-Eastern and Eastern states led to 51% yield enhancement.

Under Technology Demonstration component of NICRA, location-specific climate resilient technologies have been tested and validated at on-farm sites of 151 climatically vulnerable districts for adoption by the farmers. One village cluster from each of the 151 districts was selected by the respective Krishi Vigyan Kendra (KVK) in the district and the program is implemented through farmer participatory approach. The technologies developed through active participation of farmers and other stakeholders are ready to be integrated with the developmental programs of different

Ministries, so that they reach large number of farmers and secure their livelihood under climate change conditions. During the past twelve years, 21,083 capacity building programs were conducted throughout the country under NICRA project to educate stakeholders on various aspects of climate change and resilient technologies, covering 5,98,529 different stakeholders including farmers so as to enable wider adoption of climate resilient technologies.

Even though India's contribution to global warming is minimal, it has done far more than its fair share in addressing the climate change by implementing above mentioned schemes by taking a lead in climate resilient agriculture. India strengthening its climate resilience by lowering the carbon footprint, restoring the dwindling forest cover, promoting resilient agriculture, conserving natural resources, encouraging renewable energy resource usage and safeguarding future health. As a result, India eventually would become climate resilient country rather than climate vulnerable.

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Digital Tools for Environmental Sustainability

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Technology is reshaping our world in profound ways – and the choices we make today hold the power to influence the future of our planet. As we navigate the complex and rapidly evolving terrain of digital transformation, it is crucial to harness technology as a force for good, one that contributes to a healthier, safer, and more sustainable environment. Sustainable digital transformation consists of two main aspects, one being the digitalization of sustainability that emphasizes the proactive development and use of digital tools to achieve environmental targets by using digital technology at its maximum potential to harness positive outcomes for environmental sustainability. Another is sustainable digitalization involving the support for the development and use of technology with sustainability considerations in mind. This ensures that technological advancements prioritize ethical considerations and environmental sustainability throughout their lifecycle. Digital tools are revolutionizing the way we interact with the environment by aiding in ecosystem monitoring, critical decision-making in resource conservation, and influencing the global economy and consumer behaviour. Practicing sustainable farming through precision agriculture, promoting the use of renewable energy, limiting waste and environmental pollution, conserving precious water resources, effectively monitoring ecosystem biodiversity and geological processes, and aiding in environmental impact assessment of crucial developmental projects are some of the areas that can utilize digital tools.

Digital tools for sustainable energy use

Harnessing the power of digital tools is crucial in achieving effective energy conservation. The benefits of real-time monitoring, data-driven decision-making, automation, and behavioural change empower individuals and organizations to make a significant impact on energy efficiency. Digital tools like energy monitoring systems, smart thermostats, energy management software, and renewable energy tracking platforms are transforming the landscape of energy conservation (Energy 5, 2024). As the world shifts towards greener energy sources, digital tools play a vital role in integrating renewable energy into existing systems. By leveraging renewable energy sources, businesses and individuals can not only reduce their carbon footprint but also benefit from energy cost savings, energy independence, and reducing environmental impact by significantly reducing greenhouse gas emissions and contributing to a cleaner and more sustainable environment. By embracing these technological advancements, we pave the way for a sustainable future that optimizes energy resources and mitigates environmental impact. Digital tools are very important for sustainable energy use in the agricultural sector right from land preparation (laser land leveller) to harvesting, threshing, processing, storage, food supply chain, etc.

Digital tools for reducing GHG emissions

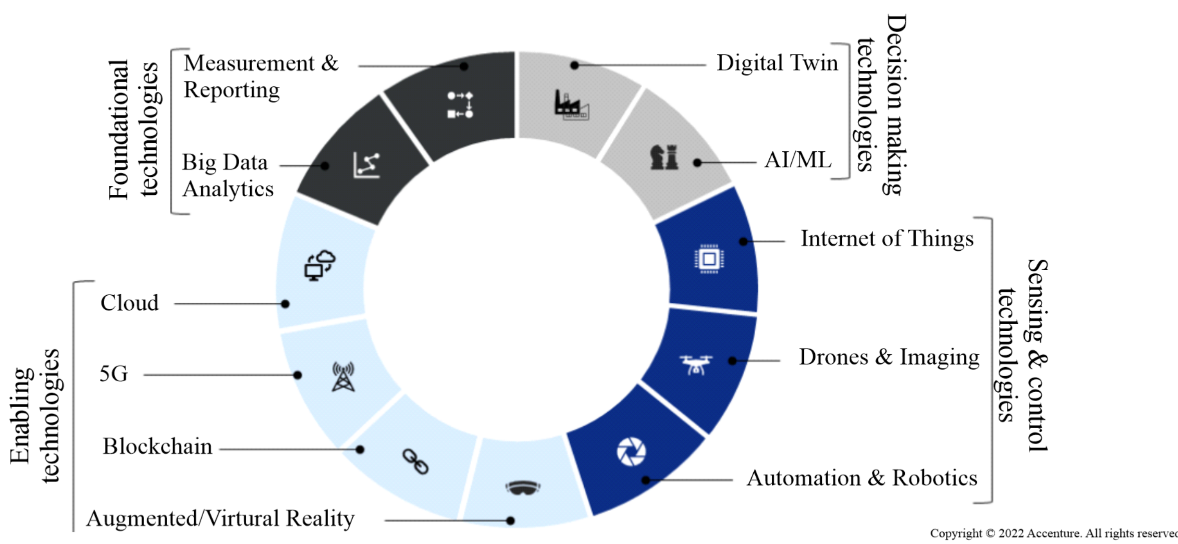
The urgency of addressing climate change is becoming increasingly apparent, with current commitments for 2030 projected to only achieve a modest 7.5% reduction in emissions. To align with the Paris Agreement goals, a far more substantial 55% reduction is required by 2030. Bridging this significant gap necessitates a profound transformation in high-emitting sectors, focusing on efficiency, circularity, and sustainability. Fortunately, digital technology emerges as a potent catalyst in expediting this essential shift.

According to an analysis conducted by Accenture in collaboration with the World Economic Forum, the potential impact of digital technologies, if widely implemented across industries, is profound. Scaling digital solutions has the potential to contribute up to 20% of the required 2050 reduction, as outlined in the International Energy Agency's net-zero trajectories. Specifically, within the energy, materials, and mobility sectors, swift adoption of digital technologies can already yield emission reductions ranging from 4–10%.

This data underscores the pivotal role that digital technology can play in meeting and surpassing environmental targets. By embracing digital solutions at a larger scale, industries can drive substantial reductions, aligning with global efforts to combat climate change and achieve a sustainable, low-emission future (George *et al.*, 2022).

Energy, materials, and mobility constitute the three highest-emitting sectors, contributing 34%, 21%, and 19% of total 2020-year emissions, respectively. They also represent sectors where digital technologies hold the highest potential to reduce emissions. These include four clusters of high-impact digital technologies:

1) Decision-making technologies that augment human intelligence
2) Sensing and control technologies that collect data and alter physical processes to be more sustainable
3) Enabling technologies that are core for any digital business today to realize benefits
4) Foundational technologies that exist within current operations.



Digital tools in biodiversity monitoring

Biodiversity monitoring is a critical aspect of conservation efforts aimed at preserving the planet's ecosystems and the many species that depend on them. Many developing countries are hotspots of biodiversity where poorly planned developments risk accelerating the species extinction rate. Thus, biodiversity monitoring becomes a critical requirement and technological development embraces the opportunities for enhancing the development of countries while safeguarding the ecosystem. Conventional methods for monitoring biodiversity rely on time-intensive and expensive practices. Surveying remote areas poses logistical challenges, and accessing the necessary expertise can be both difficult and limited. Consequently, these constraints often result in incomplete data collection and reliance on expert opinions, potentially leading to underestimations of biodiversity risks and the potential impacts on natural ecosystems. In recent years, the development of cutting-edge digital technologies and the increase in computing power opened the way to a wide range of scientific applications in the environmental monitoring field, including biodiversity monitoring and impact assessment. Very high-resolution cameras and visible, multispectral, and thermal sensors equipped on Unmanned Aerial Vehicles (UAV) and remote sensing are tools to evaluate ecosystems, assess disturbances, and analyze the dynamics and changes of biological communities (Development Asia, 2023). This allows researchers to gather data on biodiversity in remote or hard-to-reach areas that would be difficult to assess using traditional monitoring methods. Additionally, remote sensing data can be used to create maps and models that can be used to inform conservation planning and management efforts.

1. Unmanned aerial vehicles (UAVs)

Unmanned aerial vehicles (UAVs), known for their affordability and cost-effectiveness, are gaining popularity in ecological monitoring and biodiversity conservation efforts. Professionals, scientists, and even environmentally conscious individuals are employing drones equipped with high-resolution cameras and a variety of sensors, including visible, multispectral, and thermal sensors. These drones are instrumental in evaluating ecosystems, gauging disturbances, and studying the dynamics and alterations within biological communities (Hodgson *et al.*, 2016). Furthermore, there is a growing trend in utilizing images captured by drones in conjunction with advanced deep-learning algorithms for more comprehensive analysis and insights. In the present scenario, it is one of the important digitals which can be mostly used for environmental sustainability.

2. Remote sensing (RS)

Utilizing satellites and various remote sensors, remote sensing technology captures data on critical environmental factors such as land use and vegetation cover. Subsequent processing and analysis of this data yield valuable insights into the well-being and diversity of species and ecosystems. A notable advantage of remote sensing technology lies in its capacity to cover expansive areas swiftly and efficiently. This capability enables researchers to acquire biodiversity data in remote or challenging-to-access locations, which would prove arduous using conventional monitoring techniques. Furthermore, the data derived from remote sensing can be leveraged to generate maps and models, offering essential information to guide conservation planning and management initiatives. Therefore, remote sensing digital tools are very important for future planning of environmental sustainability.

3. Environmental DNA (eDNA)

Environmental DNA (eDNA) refers to genetic material sourced from environmental samples like soil, water, or air, without the need to directly capture or observe the organism. Various animals, including humans, release genetic material through shedding fur, skin fragments, and other organic substances, each carrying a unique DNA signature specific to its species. Recent advancements enable scientists to amplify these fragments, sequence the genetic material, and cross-reference the obtained results with extensive databases containing genetic sequences of numerous species.

The eDNA tool proves exceptionally valuable when surveying for the presence of elusive or rare species, including those that are endangered or cryptic and challenging to detect through traditional direct or indirect observation surveys. Additionally, it serves a crucial role in monitoring the existence of invasive species. In scenarios where eradication programs are underway, the tool aids in verifying the effectiveness of such initiatives. The sampling process is user-friendly, allowing unskilled operators to collect samples for subsequent laboratory analysis. This approach reduces the necessity for organizing intricate field expeditions involving international experts. There are still cons, such as the absence of some species in the DNA database (especially the rarest ones and undescribed species) and the analysis may just confirm the presence of the species but not determine its abundance. Hence, this digital technology can be a boom for future environmental harmony and sustainability.

4. Acoustic monitoring

A promising avenue for biodiversity monitoring involves the recording and analysis of sound. Specialized microphones and software enable researchers to detect and track the vocalizations of various species, offering valuable insights into ecosystem health and diversity. Acoustic monitoring, also known as Ecoacoustics, is not a novel approach; it has been employed for decades to identify the presence of cetaceans and bats, among other species. Distinctive calls of birds, frogs, and insects serve as identifiable markers for monitoring their presence.

For instance, analyzing bird song recordings allows researchers to differentiate between species and observe changes in their breeding patterns and habitat utilization over time. Similarly, monitoring bat calls enables the identification of different species, tracking their migration patterns, and studying the impact of environmental factors like habitat loss and climate change on their populations. Establishing an "acoustic baseline" or "Acoustic Index" for a specific area facilitates the monitoring of relative biodiversity, assessing whether a particular development or habitat restoration yields expected results (Stowell and Sueur, 2020). Moreover, the automated detection of harmful or illegal activities, such as logging and hunting, can trigger real-time alerts to authorities.

5. Biodiversity modelling

Environment practitioners are used to doing mathematical modelling to calculate the impacts of development projects on air and water quality, noise, and hydrology, among others. Impacts on biodiversity are more difficult to model, mostly due to the complexity of biological interactions and the lack of reliable species distribution and habitat composition data. Biodiversity models can be used to understand the factors that influence species distribution and abundance, predict the impact of environmental changes—such as the construction of a road and inform conservation and management decisions. In the future, biodiversity modelling will play a crucial role in environmental sustainability.

Digital tools for sustainable waste management

Digital tools like smart bins, IoT sensors, and AI applications in image recognition can help in monitoring waste generation, recycling, and smart waste management by increasing efficiency and sustainability in waste handling and resilient and environmentally conscious waste management. Robotics, IoT, cloud computing, AI, and data analytics have a major impact on the efficiency and sustainability of the waste management industry (EEA, 2021).

1. Robotics

Process: Advancement in pneumatic sorting as a result of automation technology allows the production of defined waste streams of high purity (over 90%)

Example: Robots that can identify and sort recyclables and critical materials through image recognition/ IR scanning/ AI vision systems when dismantling used phones/ electronics

2. AI and neural networks

Process: Machine learning- using neural networks based on the use of data to solve problems without explicit programming is used for classification and pattern recognition in the waste management context, improving the efficiency of sorting.

Example: Autonomous, self-driving street sweepers, refuse trucks.

3. IoTs

Process: As more and more devices are connected to the internet or other networks, sensor-supported containers can collect data and transfer it to central units.

Example: Smart waste bins with identification systems, weighing systems, level sensors, temperature sensors, and software for optimizing logistics.

4. Cloud computing

Process: Storing and processing of sensor data and cloud-based software solutions make it easy to optimize workflows and document failure to collect, sort, or detect waste bins that are not paid for

Example: Cloud-based software for:

- Connection, standardizing, and optimizing internal procedures
- Real-time order management, route planning and optimization, customer self-service, order-tracking and evaluation

5. Data analytics

Process: Processing and analyzing data play an important role in the recycling industry to identify patterns, extract information, discover trends, or calibrate models. This knowledge is important to evaluate different options for the transition to a recycling economy

Example

- Electronically supported deposition of waste collection vehicles
- Evaluation of sensor data for automated sorting plants
- Control of waste incineration plants
- Drone-based data collection on landfills

Digital tools for sustainable agriculture

Digital tools have revolutionized the way agriculture is practiced, making it more sustainable and efficient. Precision agriculture tools like GPS-guided tractors and drones equipped with sensors and cameras allow farmers to precisely target inputs such as water, fertilizer, and pesticides, reducing waste and minimizing the environmental impact. Mobile apps and online platforms provide farmers with real-time weather data, market information, and farming best practices, enabling them to make informed decisions and optimize their yields. Blockchain technology is also being used to increase transparency and traceability in the supply chain, ensuring that food is produced sustainably and ethically.

1. Remote sensing and satellite technology

In sustainable farming, remote sensing and satellite technology are crucial tools. They help monitor crops, soil, and important factors from a distance. By using indices like NDVI, they offer information on crop health, growth, and stress, helping detect pests early and optimize irrigation. These technologies also assess soil health, examining key parameters such as soil organic carbon (SOC), N, P, and K. This data guides accurate fertilizer use, minimizing nutrient runoff and emissions, and boosting overall crop productivity.

2. Farm management through enterprise Resource Planning (ERP)

Adopting farm management through an ERP system provides farmers with a centralized digital platform for their entire supply chain. This platform helps track input consumption, including fertilizers, pesticides, and fuel use. By utilizing the data collected, farmers can optimize resource usage, leading to a reduction in emissions per unit of production. The real strength of Farm Management ERP systems is their capacity to offer farmers a holistic view of their operations, facilitating data-driven decisions that minimize environmental impact while maximizing efficiency (Shinde, 2023).

3. IoT sensors

Internet of Things (IoT) sensors have transformed agriculture by providing real-time data for informed decision-making. These sensors, covering aspects like soil, nutrition, and livestock, play a crucial role. Weather data aids in predicting patterns, optimizing planting, and harvesting times, and cutting down on energy consumption and emissions. Soil sensors offer details on moisture and nutrient levels, allowing precise irrigation and fertilization. Livestock sensors enhance resource management and minimize environmental impact by monitoring animal health and behaviour. This technology signifies a new era in agriculture, promoting efficiency and environmental sustainability.

4. Weather and climate data

Having access to precise weather and climate data is crucial for sustainable agriculture. Advanced tools for weather forecasting and modelling assist growers in optimizing planting and harvesting schedules, leading to reduced energy consumption and greenhouse gas (GHG) emissions. Aligning agricultural activities with weather patterns enables growers to effectively mitigate risks and adapt to changing conditions. Climate data supports long-term planning and decision-making, helping growers choose crops and practices that are resilient to climate change, contributing to lower emissions.

5. Carbon accounting tools

Growers seeking to evaluate and diminish their greenhouse gas (GHG) emissions find specialized carbon accounting tools indispensable. These tools compute emissions from diverse sources like energy use, transportation, and land use changes. Offering a thorough overview, carbon accounting tools enable growers to pinpoint reduction opportunities and make informed decisions on carbon offset initiatives. Moreover, these tools ease participation in carbon credit programs and other market-based mechanisms that reward emissions reductions.

6. Integration of technologiesTop of Form

The combination of Remote Sensing and Satellite Technology, Machine Learning & AI, and IoT sensors in agriculture signifies a comprehensive approach. This abundance of information enables data-driven decisions to optimize resource utilization and reduce emissions. Machine learning and AI analyse extensive datasets to identify patterns related to greenhouse gas (GHG) emissions, empowering farmers to take proactive measures to reduce their carbon footprint. IoT sensors, including weather stations, soil sensors, and livestock sensors, offer real-time data essential for timely decision-making, ensuring that the optimization of agriculture businesses aligns with the principles of people, planet, and profit.

Overall, digital tools have the potential to transform agriculture into a more sustainable and profitable industry, and environmental sustainability while also contributing to global food security.

Conclusion

Embracing the potential of technologies such as IoT, AI, and data analytics empowers individuals, businesses, and nations to make informed decisions, reduce environmental impact, and foster a more sustainable world. As we continue to explore and adopt these advancements, we must prioritize ethical considerations and ensure that digital transformation aligns with the principles of environmental stewardship. Through these collective efforts, we can forge a path toward a harmonious coexistence between technology and the environment, creating a legacy of sustainability for generations to come in the future.

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Digital Technologies for the Management of Rainfed Agriculture

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The diverse landscapes of agriculture refers to irrigated and rainfed. Rainfed agriculture is a type of farming system that relies predominantly on rainfall for crop production. Rainfed agriculture covers a significant portion of the world's agricultural land, particularly in arid and semi-arid regions. Rainfed agriculture plays a crucial role in global food production, as it supports the livelihoods of millions of farmers worldwide. In addition, rainfed agriculture helps to sustain rural livelihoods and ecosystems. Rainfed farming systems often preserve biodiversity and natural resources, as they are less intensive than irrigated agriculture. It is practiced in regions where the availability of water is limited, and the success of agricultural activities is largely dependent on the timing, amount, and distribution of rainfall. Tailoring agricultural practices to diverse rainfall zones like low, medium and high ensures a sustainable approach to cultivation. Rainfed agriculture has a ballet of diverse facets in resilience and adaptability for its sustainability. To keep rainfed agriculture sustainable, it is required to analyse its characteristics, understand challenges and integrating traditional wisdom with modern agricultural techniques to navigate the complexities of this dynamic farming method for sustainable income to the farming community.

Characteristics and Challenges of Rainfed Agriculture

Rainfed agriculture relies entirely on rainfall for watering crops. Farmers have to adapt their planting and harvesting schedules based on seasonal rainfall patterns. Farmers typically choose crops that are well-suited to the local climate and rainfall patterns. Drought-resistant crops are often preferred in regions prone to erratic or insufficient rainfall. Since water is a limited resource in rainfed agriculture, farmers often employ water conservation techniques such as mulching, contour ploughing, and terracing to maximize moisture retention in the soil. Rainfed agriculture is highly susceptible to climate variability, including droughts, floods, and erratic rainfall patterns. Farmers practicing rainfed agriculture often employ various risk management strategies, such as crop diversification, soil conservation practices, and reliance on traditional knowledge to cope with unpredictable weather conditions. Compared to irrigated agriculture, rainfed agriculture typically yields lower productivity per unit of land due to its dependence on rainfall, which can be unpredictable and unevenly distributed.

Rainfed agriculture faces several challenges that can impact productivity, sustainability, and food security. Climate change can exacerbate the challenges, leading to increased uncertainty for farmers. Rainfed agriculture is highly dependent on rainfall, making it vulnerable to climate variability and change. Erratic rainfall patterns, droughts, floods, and extreme weather events can adversely affect crop yields and livelihoods. Poor water management practices and competition for water resources from other sectors. Continuous reliance on rainfed agriculture without adequate soil conservation measures can lead to soil erosion, nutrient depletion, and declining soil fertility. Soil degradation reduces crop yields and exacerbates land degradation. Farmers in rainfed regions often face challenges in accessing quality seeds, fertilizers, and pesticides due to poor infrastructure, limited market access, and high input costs. This hampers their ability to maximize productivity. Limited technological advancements and extension services in rainfed agriculture hinder the adoption of modern farming practices. Farmers may lack knowledge about improved crop varieties, sustainable land management techniques, and efficient water use practices. Many rainfed areas are characterized by high levels of rural poverty and food insecurity. Limited economic opportunities, inadequate infrastructure, and lack of social services contribute to the perpetuation of poverty cycles. Insecure land tenure and unclear property rights can hinder investments in rainfed agriculture. Limited market infrastructure and poor connectivity to markets restrict farmers to sell their produce at fair prices. Inadequate storage facilities and transportation infrastructure contribute to post-harvest losses and reduce farmers' income. Addressing these challenges requires a holistic approach that integrates climate-resilient farming practices, improved water management strategies, enhanced access to inputs and markets, and supportive policies that prioritize the needs of smallholder farmers in rainfed areas.

Digital Technologies

Digital technologies encompass a wide range of tools, systems, and platforms that utilize digital information and communication technologies to perform various tasks, solve problems, and enhance efficiency in different domains such as:

The internet serves is the backbone for many digital technologies, enabling connectivity and communication between devices, systems, and users worldwide. Mobile Devices provide access to a multitude of digital services, applications, and information on-the-go. Computing devices process and store digital data, running software applications and facilitating complex computations. Software applications, or apps, encompass a wide range of programs designed to perform specific tasks, such as word processing, data analysis, data dissemination, and more. Big data technologies process and analyse large volumes of data to extract insights, patterns, and trends, enabling data-driven decision-making and predictive modelling in various fields. AI and ML technologies enable computers and systems to perform tasks that traditionally require human intelligence, such as natural language processing, image recognition, pattern recognition, and autonomous decision-making. Internet of Things (IoT) technologies connect physical objects, devices, and sensors to the internet, allowing for remote monitoring, control, and optimization of processes and systems in various domains, including smart cities, agriculture, and manufacturing. Blockchain technology enables secure, transparent, and decentralized digital transactions and record-keeping through distributed ledger systems, with applications in cryptocurrency, supply chain management, voting systems, and more. These are just a few examples of digital technologies, and the landscape continues to evolve rapidly with ongoing advancements and innovations in technology and computing.

Employing Digital Technologies for Sustainable Management

Digital technologies have revolutionized various aspects, including agriculture. In rainfed agriculture specifically, digital technologies offer solutions to the specific agroecological conditions to improve efficiency, productivity, and resilience. Some of the ways to apply digital technologies in rainfed agriculture:

1. Data-Driven Decision Making

Digital technologies provide farmers with access to real-time advisories, crop growth, and market trends. This data enables informed decision-making, allowing farmers to optimize inputs, resources, and practices to maximize yields and profitability.

Weather Forecasting and Monitoring: Digital weather forecasting tools provide farmers with accurate and timely information about upcoming weather patterns, enabling them to make informed decisions regarding crop management practices,

Water Management Solutions: Digital technologies support efficient water management strategies in rainfed agriculture, such as rainwater harvesting systems, micro-irrigation techniques, and moisture sensors for irrigation scheduling. These solutions help optimize water use, minimize runoff, and mitigate the impacts of water scarcity and erratic rainfall patterns.

Soil Health Monitoring: Sensors and digital platforms allow farmers to monitor soil moisture levels nutrient content, pH, and erosion risk in rainfed areas in real-time. This information helps optimize irrigation scheduling, prevent waterlogging or drought stress, and improve water use efficiency in rainfed agriculture. irrigation scheduling, and risk mitigation strategies. implement precise soil management practices, such as conservation tillage and cover cropping, to maintain soil fertility and structure.

2. Precision and Efficiency

Digital technologies such as IoT sensors, GPS, and drones enable precision agriculture practices, where inputs like water, fertilizers, and pesticides are applied precisely where and when they are needed. This minimizes wastage, reduces environmental impact, and improves resource use efficiency.

Precision Agriculture: Digital tools such as GPS-enabled tractors, drones, and unmanned aerial vehicles (UAVs) enable precision agriculture practices in rainfed farming systems. Farmers can accurately map fields, apply inputs (e.g., fertilizers, pesticides) only where needed, and optimize resource use efficiency.

Mobile Applications: Various mobile applications provide farmers with access to agronomic advice, market prices, pest and disease management strategies, and agricultural extension services. These apps empower farmers to make data-driven informed decisions and adopt best practices for rainfed agriculture to improve livelihoods.

3. Risk Mitigation and Resilience

By providing early warning systems for weather events, pest outbreaks, and market fluctuations, digital technologies help farmers mitigate risks and adapt to changing conditions. Predictive analytics and decision support tools assist farmers in planning and implementing strategies to minimize losses and maximize resilience.

Remote Sensing and Satellite Imaging: Satellite imagery and remote sensing technologies provide valuable data on crop health, vegetation indices, soil moisture content, and land use patterns. Farmers can use this information for crop monitoring, yield forecasting, and identifying areas of stress or nutrient deficiencies.

Crop Modelling and Decision Support Systems: Advanced computer models and decision support systems simulate crop growth, water requirements, and yield predictions under different environmental scenarios. Farmers can use these tools to assess risks, plan crop rotations, and optimize resource allocation in rainfed farming systems.

4. Data Analytics and Decision Support Systems

Advanced analytics and decision support tools process large volumes of data from diverse sources, such as weather stations, satellite imagery, and farm sensors, to generate actionable insights for farmers. *AI and ML*: AI and ML algorithms process large volumes of agricultural data to generate insights and predictions. Predictive models for yield forecasting, disease detection, pest monitoring, and market trends help farmers optimize production, reduce losses, and make strategic decisions. These tools can optimize farm management decisions, such as crop planning, resource allocation, and risk management, based on real-time data and predictive modelling.

Internet of Things (IoT) Sensors: IoT sensors embedded in soil, crops, and farming equipment provide real-time data on environmental conditions, crop health, and equipment performance. This data-driven approach facilitates proactive management decisions and enhances productivity and sustainability in rainfed agriculture.

5. Market Access and Transparency

Digital marketplaces, e-commerce platforms, and blockchain technology facilitate transparent and efficient transactions between farmers, buyers, and consumers. These platforms improve market access, enable fair pricing, and provide traceability and quality assurance throughout the supply chain, enhancing consumer trust and confidence.

Blockchain Technology: Blockchain technology can enhance transparency and traceability in agricultural supply chains, ensuring fair prices for farmers and improving market access. Smart contracts and digital payments enable secure transactions and reduce inefficiencies in rainfed agriculture markets.

6. Sustainability and Environment

Digital technologies support sustainable agricultural practices by promoting soil health, biodiversity, and natural resource conservation. Through precision agriculture, farmers can minimize the use of inputs, reduce greenhouse gas emissions, and adopt practices that enhance ecosystem services and resilience to climate change.

Farm Management Software: Integrated farm management software platforms offer comprehensive tools for planning, monitoring, and analysing farm operations. Farmers can manage tasks, track inputs and outputs, and generate reports to optimize productivity and profitability in rainfed agriculture.

Crop Selection and Management: Digital tools provide data-driven insights into crop suitability and performance under varying rainfall conditions. Farmers can access information on drought-tolerant crop varieties, planting calendars, and agronomic practices tailored to their specific agroecological zone, enhancing crop resilience and yield stability.

7. Capacity Building and Knowledge Sharing

Digital technologies deliver agronomic advice, training, and extension services to farmers through mobile apps, SMS alerts, and online platforms. These tools disseminate best practices, research findings, and market information, empowering farmers with knowledge and skills to improve their practices and livelihoods.

Digital Extension Services: Online training modules, webinars, and virtual field days provide accessible and cost-effective extension services to farmers in remote rainfed agriculture regions. Digital platforms facilitate knowledge sharing, capacity building, and networking among farmers, researchers, and agricultural experts.

Conclusion

Despite its challenges, rainfed agriculture plays a crucial role in global food production, providing livelihoods for millions of people, particularly in rural areas of developing countries. The veery purpose of using digital technologies in agriculture is to harness the power of data, connectivity, and innovation to transform traditional farming practices, improve productivity and livelihoods, and create a more sustainable and resilient food system for future generations. By leveraging digital innovation, agriculture can become more efficient, equitable, and environmentally sustainable, contributing to global food security and economic development. Farmers can overcome the challenges posed by climate variability, water scarcity, and resource constraints from informed decisions. However, it's essential to ensure that these technologies are accessible, affordable, and tailored to the needs and contexts of smallholder farmers, fostering inclusive and equitable development in rural communities.

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Climate Resilient Integrated Farming Systems for Enhancing Livelihood of Small and Marginal Farmers in of the Middle Indo-Gangetic Plains

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Worldwide demand for agricultural products is projected to rise by 70% for food items and nearly double for livestock products by 2050, in response to the estimated population growth to 9.5 billion (Goldstone, 2010). The researchers and policymakers face a dilemma in providing food for the growing population, as over 80% of the available land has already been used for farming and other development purposes (Young, 1999). In the 21st century, our country's other industries have grown faster as a share of the economy. With human population pressure and declining per capita land availability globally, and no horizontal extension of land for farming, farming system techniques must be modified (FAO, 2018). Due to limited feed availability and the impact of climate pressures, livestock productivity is anticipated to suffer adverse consequences (Kakamoukas *et al*., 2021). Both farmers and researchers must discover an effective, environmentally-friendly, and cost-effective approach to enhance the ability of agriculture to withstand the impacts of climate change and the combined effects of livestock on the system. In this context, integrating agricultural components as a "system" with effective soil, water, crop, animal, and pest management techniques is essential for sustainable growth in agriculture. These systems should be environmentally sustainable, economically efficient, and have mutually advantageous components. Integrated agricultural System (IFS) is the practice of combining various agricultural components, such as crops, livestock, and associated subsidiary industries, to optimize nutrient consumption and reduce negative environmental impacts (Babu *et al*., 2023). The production system is characterized by interdependence, interconnectedness, and frequent interlocking. The IFS idea is centred on optimizing the use of main and secondary products from one component as input for another component, resulting in reciprocal benefits and integration within a unified system. The IFS strategy ensures the stability of revenue streams by effectively managing natural resources and promoting diversity of livelihoods. The integration of agricultural, aquaculture, and livestock farming systems is a long-standing practice historically employed by farmers in India and China. Nevertheless, in recent decades, there has been a shift towards employing scientific methods to enhance the popularity and resilience of the IFS by carefully choosing appropriate components.

IFS Concepts

IFS systems combine livestock, aquaculture, agriculture, and agro-industry in an expanded symbiotic or synergistic system to use wastes from one process as inputs for others, with or without treatment, to provide energy, fertilizer, and feed for maximum productivity at low cost. Many farmers worldwide use IFS ideas. Crop, livestock, and sometimes aquaculture and trees are typical in these systems. Recycling and enhancing the use of organic wastes and crop leftovers reduces risk, increases productivity, and profitability in farming operations. Integration happens when one enterprise's outputs (typically byproducts) are used as inputs by another in farming systems. In contrast to mixed farming, integrated agricultural companies interact eco-biologically, in space and time, and support and depend on each other.

Why Farming System?

It aids in identifying farm productivity constraints. Through farmer participatory research, it provides technical interventions to improve farming systems at a specific resource base. To understand agricultural production's physical and socioeconomic environment. To understand farmers' skills, limits, preferences, and aspirations. To understand and assess essential farming systems, including their practice and performance.

Goals of Integrated Farming System

The goal is to maximize the yield of all component enterprises in order to generate a consistent and stable revenue at higher levels. Enhancing the efficiency of the system and attaining a balance in agricultural ecology. Manage the proliferation of insect pests, diseases, and weed populations by implementing natural cropping system management techniques to maintain them at a low degree of intensity. To promote a clean and healthy environment for society, it is important to minimize the use of chemical fertilizers, agrochemicals, and pesticides, which can be detrimental. This will help ensure the production of pollution-free and nutritious crops.

Advantages of IFS over traditional farming

Productivity and Profitability: Integrated farming systems boost economic yield per unit area per unit time by intensifying agricultural and allied operations. Time concept through crop intensification and space concept through vertical dimension through crops and linked enterprises boost production. The system as a whole allows one component's produce/waste to be used as input on another at the lowest cost. By reducing the cost of component two and other linked components, the profitability per rupee invested is increased by eliminating middlemen in most inputs and working out the farm's net income.

Sustainability: To satisfy the 2.2 percent annual population growth, large amounts of inorganic fertilizers, insecticides, fungicides, herbicides, etc. are dumped. Thus, soil and ecosystem pollution is likely. If the problem causes a substantial area to be destroyed, soil productivity will decrease in the future. In IFS, organic supplementation by proper use of connected component byproducts as manures can sustain the production base, soil, for longer durations.

Balanced food/nutritional supplements: IFS links diverse components to create protein, carbohydrate, fat, minerals, vitamins, and more from the same unit area. This will help solve Indian farmer malnutrition.

Pollution free environment: During crop production, certain organic materials are generated as waste. If these materials are not properly managed, they can lead to environmental pollution as they decompose. Similarly, the excessive use of fertilizers, pesticides, fungicides, and herbicides leads to significant pollution of the soil, water, and environment at a concerning level. In the context of Integrated Farming System, waste materials are efficiently utilized by connecting suitable components, thereby repurposing the byproduct as organic manures. Likewise, using bio control methods will aid in averting contamination of soil, water, and atmosphere. In regions where pig farming is a prominent industry, the disposal of pig excrement releases a significant amount of undesirable gases, leading to long-term pollution of the atmosphere. Within the IFS system, pig excrement is utilized in the biogas facility to generate renewable energy. This energy is then used for lighting, extracting water from underground sources, and powering the incubation unit of the poultry farm. Therefore, IFS plays a crucial role in preventing environmental degradation.

Recycling: The stability of IFS is achieved through the efficient recycling of products or waste materials from one component as input for another component in the program. Therefore, via the practice of recycling their own resources on the farm, the farmer has the potential to decrease production expenses, ultimately leading to an increase in the overall net revenue of the farm. Furthermore, it aids in mitigating the environmental contamination that would otherwise result from the decomposition of organic leftovers from farming activities. **Money round the year:** In contrast to traditional crop farming, which only generates income upon the sale of the harvested produce after a period of five to fifteen months depending on the crop's duration, the Integrated Farming System (IFS) ensures a continuous flow of income for farmers throughout the year. This is achieved through the regular sale of eggs, milk, edible mushrooms, honey, silkworm cocoons, and other products. This will enable the financially disadvantaged farmer to escape the control of moneylenders and other financial institutions.

Adoption of new technology: The majority of large-scale farmers possess a comprehensive understanding of the influence exerted by the new technology incorporated in the package. However, over 80 percent of farmers classified as small and marginal are unable to implement the planned sophisticated technology due to financial constraints. However, for farmers engaged in Integrated Farming Systems (IFS), the continuous sale of produce from various components such as Dairy, Mushroom, Sericulture, Fruit crops, vegetable crops, and flower production throughout the year ensures a steady flow of income at weekly or fortnightly intervals. The year-round availability of cash provides a strong incentive for small and marginal farmers to adopt technologies such as fertilizer application, pesticide and herbicide application, etc., which are included in the package. This would not be possible under conventional farming due to a lack of funds.

Solve energy and fodder, fuel and timber crisis: From 2030 AD, fossil fuel shortages will affect the entire world. Thus, an alternate energy source is needed within 3–4 decades to alleviate our energy dilemma. Through appropriate recycling, IFS can generate biogas from its organic waste. This may not fully supplement, but it can help address the energy situation. In IFS, every inch of land is used. IFS advises growing perennial fodder legume trees in borders and water courses. This approach adds legume feed and increases soil nutrients by fixing atmospheric nitrogen. IFS intensifies cropping on farmed land by adding legume fodder like cowpea as a second or third tier. These approaches will alleviate the animal component's fodder shortage. In 2020 AD, the national fuel wood demand is 400 million m3, but production is just 20 million. Industrial wood demand is 64.4 million m3 in 2020 AD, but output is just 11 million m3. Production should increase twenty-fold for fuel wood and six-fold for industrial wood. Afforestation in shrub jungles and scant forests may help. By linking agroforestry, IFS can increase fuel wood and industrial wood production without affecting field crop activity.

Avoid degradation of forests: Fuelwood and timber demand and output are far apart. This will naturally lead users to unlawfully enter the forest to bridge the gap. We have 22% less woodland than the 33% recommended for our geographical area. Such encroachments could turn our woodland into a wasteland in the future. Even now, about two-thirds of the forest is scant. Our country loses

5,374 million metric tonnes of built-up soil annually. This exceeds the 4mt/ha/year average fourfold. Agroforestry in IFS can reduce forest degradation by supplementing fuel and timber wood. Keeping the catchment eco-system intact protects precious built-up soil from erosion.

Employment generation and improved literacy rate: By combining crop and animal businesses to take advantage of their complementary and supplemental relationships, labor requirements would expand greatly and assist solve underemployment. IFS allows year-round family employment. Farmers who use IFS to combine fishery, sericulture, mushroom cultivation, apiary, spawn production, dairy, poultry, agri-horticulture, agroforestry, biogas production, etc. gain knowledge in each component. This will aid farmers in any task.

Provides opportunity for agri-based industries: If the output of many interconnected components in an integrated food system (IFS) is scaled up to a commercial level and there is an excess supply in the market. This stimulates the growth of related companies that focus on preserving the byproducts.

Improves the standard of living of farmers: Farmers feel equal to other professionals in the region when IFS is used to generate bio energy, produce edible mushrooms, fruits, eggs, milk, honey, vegetables, etc. for family use and commercial use. They feel their standard of life is comparable to others, which motivates them to continue farming without the hesitation of most farmers. The developed, modified, or prevalent farming system must be updated based on location specificity, farmers' preferences, and site appropriateness.

IFS models and resilient production

The production in IFS is a comprehensive strategy aimed at increasing overall farm output and effectively managing resources to achieve sustainable agricultural production, while also considering factors such as the benefit-cost ratio and environmental well-being. These models establish and maintain links between supplemental and complementary components, hence decreasing the overall cost of inputs. The objective is to achieve a consistent and robust income at elevated levels through the optimization of yields from each individual component. Additionally, it facilitates the preservation of soil health by organically recycling residues. Its objective is to attain ecological equilibrium by enhancing the productivity of systems. Hence, it also seeks to alleviate the adverse effects of agriculture and cattle on the environment and climate change. They advocate for organic farming by limiting ecologically detrimental inputs and endorsing environmentally favourable practices such as vermicomposting and maximizing water efficiency. It enhances the ability of farming practices to withstand market price fluctuations and natural disasters.

ICAR Research Complex for Eastern Region initiatives (Kumar *et al*., 2018)

ICAR Research Complex for Eastern Region has taken initiative for development of climate resilient IFS models suited for different ecologies and developed several IFS models for different land configurations (Figure 1).

In this model, the waste land (2000m^2) has been utilized and made productive by integrating Crops + Livestock + fish/duck. Through this model the farmers' income enhanced by 356 percent with ample food and nutrition of the farm family. Likewise, some other integrations were also made and tested as on station trial and on the farmers' fields. The brief details of different integrations are depicted below as Table 1.

Before intervention

Integration

After the intervention

Figure 1. Half acre IFS model at Chakramdas village in Vaishali district of Bihar

Table 1. Annual net return and Income Sustainability index of different farming systems (Kumar *et al.*, 2018) developed by ICAR-RCER, Patna

IFS components	RGEY (t)	Gross Income (Rs.)	Net Income (Rs.)	B:C ratio	Man-days	I.S.I.
Rice - wheat	8.1	105650	30534	1.4	237	-0.037
Crop + goat	13.5	189000	77449	1.7	322	28.9
Crop + cattle	15.5	201350	72950	1.5	405	21.3
Veg. + goat	19.0	254845	139414	1.8	452	75.1
Hort. + Cattle	19.9	259690	116585	1.8	535	58.7
Crop + poultry	18.4	238985	96425	1.7	390	44.9
Crop + goat+ fish	18.9	245720	99524	1.7	333	47.0
Crop +goat + fish + duck	23.6	306840	142214	1.8	398	77.2
Crop + cattle + fish	16.2	211030	77030	1.6	435	31.7
Crop + cattle + fish + duck	18.5	242530	100530	1.7	470	47.7
Crop + goat + poultry	22.8	296445	140614	1.8	416	75.7
Crop + goat + poultry + mush.	24.5	318240	144315	1.9	439	79.8
S. D.	18.6	43247.9	30588.7	0.14	64.4	-
C.V.	10.8	17.8	29.6	8.5	15.4	-

Climate resilient IFS models (Kumar *et al.*, 2021)

IFS model	Components	Area	System Income (Av.)	Income (Rice-Wheat)	Fert. Saving (%)	Add. Emp. over R-W	Location
Vegetable-based	Veg. + Backyard fish/ duck + goat	2000 m^2	52,000-58,000	15,000-18000	24.5	56	Chakramdas Vaishali
Livestock-based	F. Crops + Hort.+ goat + Poultry + mushroom	4000 m^2	80,000-1,10,000	30,000-35,000	22.7	135	ICAR-RCER, Patna &. Nalanda dist.
Pond-based (lowland)	F. Crops + Hort.+ Cows + Fish/duck	8000 m^2	1,50,000-2,18,000	60,000-70,000	28.4	234	ICAR-RCER, Patna & Nalanda
Pond-based (Flood prone)	F. Crops + Hort. + Fish/duck	8000 m^2	1,28,000-1,48,000	42,000-50,000	16.5	148	Motihari
Orchard/ Tree based	Rice + HD Orchards + Apiculture + Duck + Poultry + Hedge row spp.	8000 m^2	88,000-1,68,000	60,000-70,000	25.2	167	Ranchi

Novelty of the developed models

- Adoption of IFS, reduced consumption of synthetic fertilizers by 22-30% through resource recycling within the system.
- Organic Carbon in the soil increased by 6-11% due to IFS activities in a time span of 10 years.

Half acre IFS model (Crops + Livestock + Fish + Duck): 2000m^2

One acre IFS model (F. Crops + Hort.+ goat + Poultry + mushroom): 4000m^2

Two-acre IFS model (F. Crops + Hort.+ Cows + Fish/duck): 8000m^2

Two acre Orchard/Tree based IFS model (Rice + High density orchards + Apiculture + Duck + Poultry + Hedge row spp): 8000m^2

Two-acre IFS model for flood prone areas (F. Crops + Hort. + Fish/duck): 8000m^2

Fig. 2. View of developed models for different ecologies

- Adoption of IFS enhanced income by 87-352% over the dominant rice-wheat cropping.
- All models found Carbon –Ve in terms of Co_2 equivalent in view of GHG emission.
- Input energy: output energy ratio is 1:3 & 1: 2.3 for one- and two-acre IFS models, respectively.
- Man-days requirement enhanced by 180- 325 percent over Rice- wheat system
- Curtailing the cost of production upto 22-27 percent over R-W system

Constraints in adoption of IFS approach at field level

Depending on the type and size of independently owned operation, some limiting factors are:

Economies of scale: Larger farms are able to bargain more competitively, purchase more competitively, profit from economic highs, and weather lows more readily through monetary inertia than smaller farms.

Cost of inputs: fertilizer and other agrichemicals can fluctuate dramatically from season to season, partially based on oil prices; a range of 25% to 200% is common over a few year periods.

Fuel prices: Directly (for farm machinery) and somewhat less directly (long distance transport; production cost of agrichemicals), the cost of oil significantly impacts the year-to-year viability of all mechanized conventional farms.

Commodity futures: the predicted price of commodity crops, hogs, grain, etc., can determine ahead of a season what seems economically viable to grow.

Technology user agreements: a less publicly known factor, patented GE seed that is widely used for many crops, like cotton and soy, comes with restrictions on use, which can even include who the crop can be sold to.

Wholesale infrastructure: A farmer growing larger quantities of a crop than can be sold directly to consumers has to meet a range of criteria for sale into the wholesale market, which include harvest timing and graded quality, and may also include variety, therefore, the market channel really determines most aspects of the farm decision making.

Availability of financing: Larger farms today often rely on lines of credit, typically from banks, to purchase the agrichemicals, and other supplies needed for each growing year. These lines are heavily affected by almost all of the other constraining factors.

Government economic intervention: In some countries, notably the US and EU, government subsidies to farmers, intended to mitigate the impact on domestic farmers of economic and political activities in other areas of the economy, can be a significant source of farm income. Bailouts, when crises such as drought or the "mad cow disease" problems hit agricultural sectors, are also relied on. To some large degree, this situation is a result of the large-scale global markets farms have no alternative but to participate in.

Government and industry regulation: A wide range of quotas, marketing boards and legislation governing agriculture impose complicated limits, and often require significant resources to navigate. For example, on the small farming end, in many jurisdictions, there are severe limits or prohibitions on the sale of livestock, dairy and eggs. These have arisen from pressures from all sides: food safety, environmental, industry marketing.

Real estate prices: The growth of urban centres around the world, and the resulting urban sprawl have caused the price of centrally located farmland to skyrocket, while reducing the local infrastructure necessary to support farming, putting effectively intense pressure on many farmers to sell out.

What is to be done?

Policy plays a crucial role in determining the future of family farming. While family farming has the ability to endure extremely challenging circumstances, favourable conditions can facilitate the realization of its maximum potential. The significant responsibility for policy is specifically within the governmental apparatuses, multinational forums (such as the FAO, IFAD, and other UN bodies), as well as political parties, social movements, and civil society as a collective entity. Investments made by family farmers themselves can be stimulated by ensuring their rights and allocating resources towards infrastructure, research and extension, education, market channels, social security, health, and other relevant areas. Enhancing the capacity of rural groups and movements is equally crucial. It is important to remember that family farmers, regardless of their location, are actively seeking and developing innovative solutions to challenging circumstances. Hence, it is crucial to prioritize the identification of effective answers, the development of innovative practices, the dissemination of these practices to other regions and fellow farmers, and the integration of these practices into robust processes of transformation. Concisely put, there is much work to be accomplished. The positive aspect, however, is that each individual step, no matter how small, is beneficial.

Conclusion

Integrated farming allows farmers to integrate any component with crop based on their preferences and area. It boosts farm family income and soil health with balanced nutrition. Organic residue from animal and plant wastes improves soil physical condition and productivity over a longer length of time with fewer environmental hazards and higher profit margins. It reduces farming risk. The IFS model, which includes crop components, dairy, poultry, and fishery, is most effective for irrigated agro-ecosystems in the North Eastern Plain Zone. IFS make agricultural output sustainable, profitable (3-4-folds), and productive. Resource recycling covers 90–95% of nutritional needs, lowering cultivation costs and increasing profit margins and employment. Thus, IFS is promising for food and nutritional security and will conserve resources by efficiently recycling residues and trash. Farmers' participation trials with multilevel interventions on their farms can calibrate IFS models for different natural ecosystems and subsystems.

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Integrated Soil and Water Conservation through Sensors and ICT

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ABSTRACT

Information and Communication Technology (ICT) is playing a vital role in shaping Indian Agriculture. Gone are the days when the farmer had to rely on the expertise of selected people in the locality to get advice on good agricultural practices. Presently, there are a plethora of avenues from where the farmer can get information pertaining to different agricultural activities starting from land preparation to harvesting and value addition. Such avenues *viz.* mobile applications, decision Support Systems, Internet of Things (IoT) enabled integrated sensing systems besides the audio visual data shared in social media pertaining to agriculture in general and management of natural resources in particular are gaining momentum. Soil and water conservation is an important aspect of management of natural resources to not only enhance agricultural productivity but also save water and preserve the soil health. Moreover, the sensors used in agriculture for acquisition of soil moisture, soil and water quality parameters besides measurement of water passing through pipes and open channels are gaining wide applicability these days to assist in judicious irrigation scheduling besides holistic management of soil and water resources for attaining sustainability in agriculture. Agriculture during post green revolution era is facing a technological fatigue due to improper management of crop and soil health, reduced input use efficiency and yield losses of agricultural produce. Keeping this in view, the present chapter focuses on the sensors and integrated sensing devices besides the ICT tools available for soil and water conservation and agricultural water management activities for sustaining land productivity.

Key words: ICT; Sensors; Soil Conservation; water conservation; agricultural water management; Hydrology

Introduction

Agriculture is by far the largest consumer of water, with about 70% of all freshwater withdrawals being used in irrigation (UNESCO, 2020). In water scarce regions, irrigation is fundamental to fulfill crop water requirements, increase food productions through higher yields, meet the growing food demand, ensure food stability, and increase prosperity of rural areas. However, inefficient practices often lead to increased nutrient leaching, enhanced runoff and soil erosion, salinity build-up in the root zone, and the eutrophication of water bodies with associated biodiversity loss. Agricultural consumption of scarce water resources further faces an increasing competition from the multiple demand from different uses (urban consumption, industries, recreational), which makes it even more essential to improve water use efficiency in irrigated fields to cope with the increasing scarcity and contribute to the sustainability of agricultural systems. The scientific community have attempted in developing technologies for its judicious management leading to saving of this precious resource besides use of sensors in data acquisition and subsequent management. Besides this the spatial and non-spatial decision support systems (DSS), mobile interfaces, operational module of sensors and its integration with Internet of Things (IoT) enabled systems leading to near real-time or real time data acquisition and generation of alternate scenarios are being developed and validated at different locations. Besides this, policy issues pertaining to management of riparian zones near the river ecosystem, infusion of total maximum daily load concept to ensure release of good quality of water from a non-point source pollution environment i.e. agricultural fields to the downstream reservoirs to reduce eutrophication problem needs prime attention. Moreover, to come up with a scientific solution to these issues and prepare policy guidelines for management of soil and water resources, there is a need of periodic data acquisition using sensors and ICT tools. There is need of suitable sensors and integrated sensing devices to acquire data of soil moisture content, soil erosion, the flow depth and velocity in both pipped and open channel flow, surface runoff and sediment loss from watersheds, specific soil and water quality parameters, automated operation of flow in the canal commands besides automated irrigation using surface and micro-irrigation methods. Further, the data acquired from sensors can be stored in a data logger for subsequent analysis or can be transmitted on real time basis through IoT protocols for its analysis and display of results using a digital interface or in mobile platform. The mobile applications designed for a specific purpose viz. irrigation scheduling can be

Similarly, the soil erosion issues in India coupled with depletion of soil nutrients, salinity and desertification issues are of major concern and necessitates timely intervention to enhance soil fertility and ensure growth of plants. Crop rotation, cover crops, conservation tillage, and installed windbreaks are methods for better soil conservation that have an impact on both erosions as well as fertility. Policy issues on the adoption of best management practices including reduced tillage, winter cover crops, plant residues, as well as use of organic manures besides use of nano technology in fertilizer formulation and filtration techniques for better water quality. There are several digital sensing systems, interfaces and DSS for use in soil developed for soil and water conservation measures, enhancing water productivity under saline environment and under irrigated rice-wheat cropping system besides specific irrigation water management modules at regional scales. However, DSS still fail in many regions of the world due to a perceived gap between research and farming practices, farmers' mistrust in the embedded technology, and limited access of on-farm water management technologies.

Integrated sensing systems and ICT based tools in soil and water conservation requires the hardware and software tools for their integration besides an user friendly interface to display the result under desired scenarios. In this context, to make the system realistic, the calibration and validation of sensors and their integration with IoT for display of result and its interpretation to generate solutions is of prime importance. Application of ICT in agriculture and development of sensing systems are highlighted in subsequent section.

Sensors in Irrigation Water Management

A sensor is a device, module or a subsystem whose purpose is to detect events or changes in its environment and send the information to other electronics, frequently a computer processor. Sensors used for irrigation scheduling may include soil moisture, soil salinity, soil temperature, canopy condition, weather parameters etc. in order to help in precise decision taking. The sensor values can be used in a decision support system to automate irrigation process based on crop water requirement. Different types of sensors used for soil moisture estimation is shown in Fig.1.

WATERMARK porous block based soil moisture sensor	IRROMETER Tensiometer sensor	Neutron probes	Capacitance FDR sensor	Impedance FDR sensor	TDR sensor	TDT sensor

Figure 1. Types of sensors used for soil moisture estimation

Microcontrollers, SOCs, Single board computers

A microcontroller is a small computer on a single integrated circuit. It has one or more processors along with memory and programmable input-output peripherals. One of the widely use simple microcontroller is 'ATmega microcontroller'. Microcontrolers were originally programmed in assembly languages, but those can be programmed using high level languages like c, python and JavaScript. An Integrated Development Environment (IDE) is used for programming microcontrollers. More sophisticated are the System on Chip (SOC), which is a highly embedded integrated circuit having all the components of a computer/electronic system like microcontrol, peripherals, communication unit, GPU etc. A further advance in this line are single board computers with greater speed, larger RAM and more efficient and versatile communication peripherals. These can be programmed in higher level languages like python and Java. These are used in several automation projects and have great role in present and future of internet of things. Examples of some of these are BeagleBone, Dragonboard410c. Microcontrollers, SOCs, Single board computers have capability to get sensor inputs, analyse the input data based on programming, communicate to cloud servers or websites through different communication protocols and control operation of actuators/ devices connected to them.

Communication system

Communication in an IT based smart irrigation system involves communication of sensor values from microcontrollers to cloud servers to mobile phone app and control instruction from mobile app to cloud server to microcontroller. There are several communication protocols working on different peripherals. Communication can be done in different modes like GPRS, Wifi, Bluetooth, Zigbee, LoRa etc. based on requirement of the project and volume of data flow. Protocols like TCPIP, MQTT are used for communication over internet.

Cloud platform for data storage and transmission

Cloud platforms are used for acquisition, storage, analysis, implementation of decision support system and transmission of data from sensors and actuators. Though these works can be done using websites designed with all the required software, but that is too expensive and difficult to manage. Cloud platforms provide simple, versatile, well-managed and scalable solution for this purpose. Some of the well-known cloud platforms are Amazon web Services (AWS), Google cloud, Oracle Cloud, Fuzitsu global cloud.

Mobile application for data acquisition, analysis and display of results

Smart irrigation management, mobile applications give access to the system anytime at any place. The user interfaces of the app provide access of data from sensors/actuators and control of the actuators. Mobile apps can be developed with database management and analysis as inbuilt features, but these are kept at minimum to reduce the size of the app and its load on sharing of RAM. Android mobile phones are the most ubiquitous devices and the android application can be developed using Android SDK, basic for android, corona SDK, Delphi, visual Studio2015 etc.

More advanced multiple stakeholder oriented systems can be developed and deployed at national/state levels as described in Fig.2.

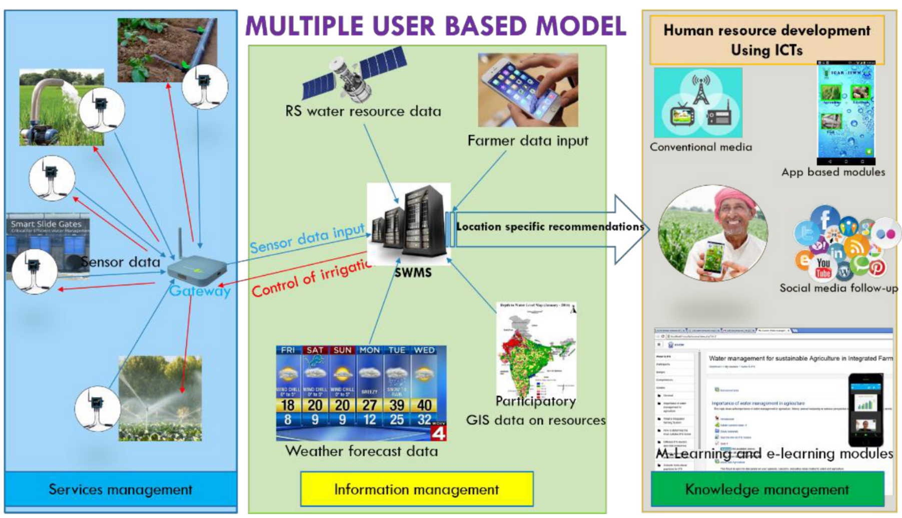

Figure 2. Schematic architecture of multiple user based IT enabled water management model

Developed IoT enabled irrigation water management system

IoT (Internet of Things) based Irrigation Water Management System (IWMS) (Fig. 3) was developed and tested in wheat and chickpea to measure the soil moisture at three different depths *viz.* 20cm, 40cm and 60cm. Installed digital soil moisture sensing system with three sensors placed at mentioned depths in chick pea is shown in Fig.6. The developed system is under testing along with the debugging of the developed mobile application for subsequent standardization.

Figure 3. IoT enabled IWMS in chick pea at ICAR-IARI farm, New Delhi

IoT enabled digital water measuring device for field channel irrigation

The digital water measuring device and the modified flume was redesigned and fabricated using aluminum sheet and the digital display unit was IoT enabled. The system was demonstrated during Krishi Mela-2022 (Fig. 8). The data of measured discharge by the device and observed using standard procedure was statistically analyzed and was observed to be having MAPE (mean absolute Percentage Error) 1.23. Value of MAPE <5) is adjudged to be the best in terms of measurement accuracy of the system.

Figure 4. Digital water measuring device at ICAR-IARI farm, New Delhi

Evaluation of an integrated soil moisture and canopy temperature sensing device for irrigation scheduling

Integrated soil moisture and canopy temperature sensing device was developed by integrating the soil moisture, air humidity and temperature sensor and the plant canopy temperature sensors along with the embedded software for their functionality (Fig.5). The soil moisture sensor of the developed system was used for scheduling of irrigation in wheat cultivar HD-2967 during *rabi* 2018-19 and 2019-20. The experiment under different irrigation regimes of field Capacity (FC), 85%FC, 70%FC, 55%FC, 40%FC during *rabi* 2018-19 resulted in water productivity of 13.2, 13.9, 14.8, 16.1 and 16.4 kg/ha.cm, respectively and irrigation water used was 342 mm (FC) to 200 mm (40%FC) (Fig.2) . The soil moisture sensor used in the integrated sensing system was calibrated using the gravimetric method and was observed to indicate the trigger point for applying irrigation under different irrigation regimes in the experiment.

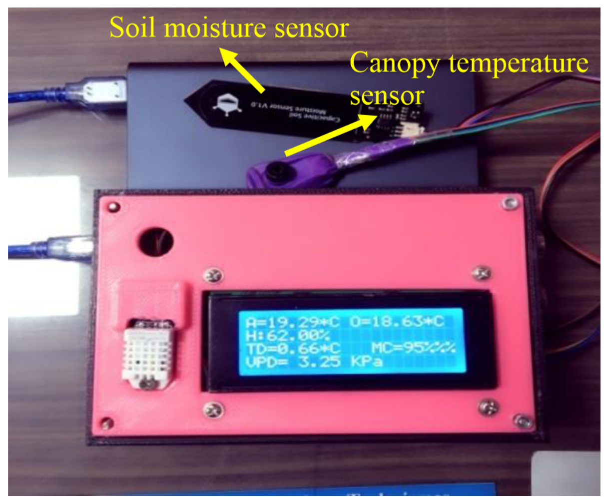

Figure 5. Integrated sensing device with soil moisture and plant canopy temperature sensors

ICT in Indian Agriculture

Many ICT based services were launched and tested in India since late 1090s. Initially the services were developed in kiosk mode using computers and internet connection. With growth of mobile network and increase in mobile penetration, many mobile based services were initiated by government as well as private organizations. Private organizations like IFFCO, TCS, Airtel etc. have initiated mobile based advisory services for farmers. Public sector agencies like Ministry of Agriculture, Tamilnadu agricultural university, ICAR, state governments like Haryana and Kerala are also providing mobile based info-advisory services for farmers. In contrast to television and radio as conventional communication media, telephone has shown remarkable growth in last decade. Kisan call centre, Lifelines India, IFFCO Kisan Sanchar Limited, mobile advisory of ICAR KVKs, Mandi on mobile service by BSNL, Market price by SMS by Rubber board, Dynamic market information by TNAU, V KVK by ICRISAT in UP and UK, Interactive information dissemination system, Mobile based agro advisory system in North-east India, m Kisan, AGMET by IMD, Intelligent Advisory system for Farmers, Kisan Kerala are some mobile based farmer advisory initiatives implemented in India.

At the same time some more sophisticated advisory systems were also developed to provide specific need-based advisory to farmers like e-Sagu that used photographs of farmers' field uploaded by agents along with detailed description of the problem. The use of human experts for solving problems was the main hindrance to scalability of the project. Some Expert Systems have been developed for different crops to forecast likelihood of occurrence of diseases and pests. Similarly, simulation models like CROPWAT have been developed to estimate crop water requirement to help in irrigation scheduling.

Irrigation water management

Precision irrigation needs estimation of appropriate soil water content, crop water requirement, weather information, crop growth stage and crop condition to precisely determine the volume of irrigation. Small scale individual farm based simple models may involve only a few information, but a system involving large number of diversified farmers need more use of artificial intelligence based decision support system to address individual irrigation requirement. Information and communication technology plays a vital role in providing precise sensor data, climatological data, participatory GIS based community resource maps, farmer inputs (specific crop/variety/growing stage) and satellite remote sensing based data (water resources/crop stress/soil moisture/ground water) for development of smart decision support system. Based on this, specific advisory can be generated for individual stakeholder groups.

Validation of the developed Decision Support System (DSS) for Irrigation scheduling in Sultanpur District, UP, India

The developed DSS for Irrigation Scheduling (Fig. 6) in rice and wheat developed in Python programming language was validated in the Naugavateer experimental site of Sultanpur (UP), India. *Sultanpur* District of UP, India. It was observed that the DSS decision assisted irrigation scheduling resulted in saving of 17% of water in rice and 10% saving of water in wheat compared to the conventional approach adopted by the farmers in surface irrigation in the experimental site. The DSS is under debugging to fix the errors. Moreover, the developed ISIS is flexible enough and can be populated with additional data base and can also be replicated to other similar agro-climatic regions with necessary modification and targeted validation.

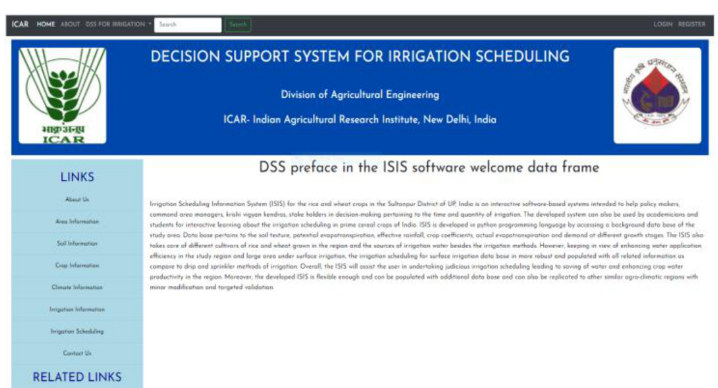

Figure 6. Captured screen of the DSS on Irrigation Scheduling

A software for irrigation scheduling in wheat, maize, soybean and mustard using single and dual crop coefficients estimated from weighing type field lysimeters

A software "*Crop Coefficient Estimator and Irrigation Scheduler (CCEIS)*" (Fig.7) (Gupta *et al.*, 2017) was developed for crop coefficient estimation and irrigation scheduling of wheat, maize, soybean and mustard crop using JAVA programming language. The background data base of the software comprised of crop coefficients of mustard, wheat, maize and soybean acquired from lysimeter experiment. It was developed using water budgeting protocol in which irrigation scheduling was suggested based on crop evapotranspiration and soil moisture information. The CCEIS software comprised of a computational module, graphic user interface (GUI) and background databases. Computational module includes calculation methods for estimation of crop coefficient values and preparation of irrigation schedules which uses soil parameters, crop parameters, climatic parameters and irrigation methods as input data. CCEIS software was tested under different scenario to predict crop evapotranspiration and irrigation scheduling of selected crops. Developed software is user-friendly having flexibility of periodic updation which can be used for judicious irrigation scheduling for enhancing water productivity of crops and cropping system of the region.

Figure 7. Captured window of the developed DSS for estimation of Kc and irrigation scheduling

DSS for enhancing productivity from irrigated saline environment

The salinization of soil and water resources in the canal commands is a serious challenge for food and nutritional security of the country. A windows based DSS program was developed bgenerate and evaluate the BMPs for given resource scenarios in irrigated saline environment for enhancing crop productivity under the NAIP-DSS Sub-Project. The developed DSS comprised of six main modules- *Crop Water Demand*, *Canal Supply*, *Groundwater*, *Irrigation Scheduling*, *Modelling*, and *BMPs* and three supporting modules- *Database and Maps*, *Constraints,* and *Farmer's Services* (Fig. 8). Six main modules were developed independently and integrated into the main DSS user interface.

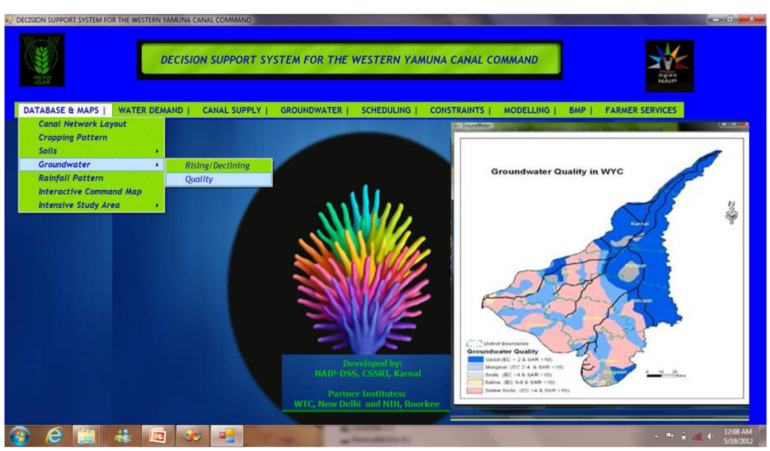

Figure 8. Captured screen of the DSS displaying shallow groundwater quality in the WYC Command

The *Database and Maps* have displayed the eight spatial thematic maps and important attributes pertaining to the developed *Irri-agro Informatics Geodatabase* for understanding the field situations/ scenarios in saline environment

DSS for different soil and water conservation practices

A DSS was developed for soil and water conservation measures using VB programming language (Fig.9) (Sarangi *et al*., 2004). The mechanical and vegetative measures available for different slopes, soil types and water availability situations around the globe were used in the data base of the DSS for soil and water conservation measures. The secondary and primary data sources were used and linked using the *if..then..else* programming construct through development of source codes in Visual Basic programming language leading to development of the DSS. Further, the programming code was compiled and the execution file was developed for use in MS windows based operating systems. Developed DSS suggest different mechanical and vegetative measures for conservation of soil and water resources. Measures to arrest soil erosion at different land slopes and conserve water for crop growth were suggested by the DSS. DSS is used for generation of different measures to conserve soil and water resources and reclaim waterlogged areas. It is used as a tool for classroom teaching and imparting training to users of DSS technologies. The software is available as *.exe file and is used in windows based operating system for use by academicians, students and line departments for subsequent disseminations to farmers.

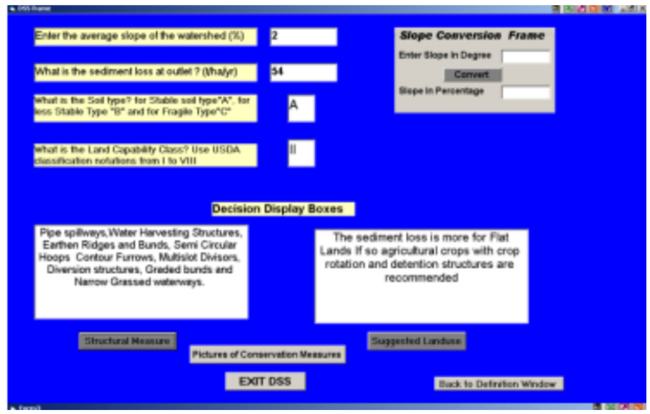

Figure 9. Captured window of the main frame of the DSS

DSS on enhancing water productivity of irrigated rice-wheat cropping system

A DSS in JAVA programming language was developed to generate alternate scenarios of grain yield, water productivity under varying irrigation regimes for different cultivars of rice and wheat. Besides this the crop water production functions generated from experimental data were used in the DSS to provide the irrigation water requirement to achieve a particular yield based on the planting method and irrigation regime for the stud region of ACR-VI. The developed DSS is flexible enough for data updation and upscaling. Besides this. Information on water saving and increase in ground water level in the RWCS regions of ACR-VI was also generated by the DSS through adoption of technologies and under changing climate.

Figure 10. Captured screen of the DSS on enhancing water productivity of irrigated RWCS

Conclusion

Agricultural water management and watershed hydrology related aspects taken up through use of sensors and ICT can not only reduce the cumbersomeness and time of undertaking the repetitive observations, but also can enhance the agricultural water productivity. Besides this, the conservation and management of the natural resources can be taken up effectively. However, the sensors used in such activities need to be properly calibrated and the correction factor or the production function need to be embedded in the integrated sensing system to enhance the accuracy of sensor. Moreover, the ICT tools need to be flexible enough to include more data from different regions to make it roust and ensure wider applicability. Further, the sensors need to be interlinked under IoT protocol to assist the stake holder in controlling the use of input in agriculture remotely in a real time mode to enhance the productivity and attain sustainability in agricultural production. Nonetheless, the digital agriculture through use of sensors and ICT tools would assist in precise application of input leading to saving of resources and making farm income sustainable and productive.

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Smart Tools in the Management of salt affected Soils

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ABSTRACT

Salt affected soil is one of the major land degradation problem of India as well as globally. To sustain land productivity, India set targets to restore 26 million ha degraded land by 2023. As such restoration of salt affected soils have the great role to achieve land degradation neutrality target (LDN). The development of smart tools and technologies offered promising solutions for managing salt-affected soils and restoring their productivity. This paper discusses some of the smart tools, which are useful to development of database on salt affected soil, devising reclamation and management strategies of salt affected soil and dissemination of management strategies through decision support system, and mobile based Apps. Combining smart tools with traditional knowledge and practices can lead to develop more comprehensive and sustainable approach for management of salt-affected soils.

Introduction

Salt-affected soils are one of the major land degradation problem, a biggest challenge to increase agricultural production and major threat to soil health and global sustainability. Globally more than one million hectare area is adversely impacted by salt affected soil. Out of this, ~424 and 833 million hectares are affected with surface soil (0-0.3 m) and subsurface soil (0.30-1 m), respectively (FAO, 2021). Further salinization is anticipated to damage 50% of all cultivated land by 2050 (Wang *et al*., 2003). In India, total area of salt-affected soils is 6.73 million ha, comprising 2.96 and 3.77 million ha saline and sodic in nature, respectively (Narjary *et al*., 2017; Mukhopadhyay *et al*., 2023). To overcome the global hunger, salt affected soils have great potential if the degraded land is restored to normal cultivable lands as new arable lands are shrinking. Salinization causes a major economic burden on the countries whose economy depends heavily on agriculture. As a result of soil salinization, global annual economic loss of agricultural production is $ 27.3 billion (Qadir *et al*., 2014). In India, due to soil salinization 16.84 million tonnes of food grain production are lost each year, costing INR 230.20 billion (Sharma *et al*., 2015). Increasing area of salt-affected soils in India has become a threat to national food security, economic development and objective of achieving land degradation neutrality. The restoration of degraded lands, particularly soils impaired by salinity, can also help to ensure the food security of the nation. However, to control spread of salt affected areas, effective management options need to be adopted because traditional methods are often laborious, energy and time consuming and may not always be sustainable. Advancements in technology offer exciting possibilities for smarter and more effective management of these soils. A paradigm shift is, therefore, needed in the research, policy and methodology of salt affected soil management to sustain food production in the country.

Following are some of the key smart tools that can be utilized for effective management of salt affected soils:

Precision Agriculture Tools

Soil sensors: These sensors measure various soil parameters like soil solution salinity (EC_{sw}), moisture content, pH, temperature and nutrient levels. By providing real-time data, soil sensors help in optimizing irrigation water and nutrient application for site-specific water, salt and nutrient management. Soil EC sensors, also known as soil electrical conductivity sensors, are the instruments used to measure the electrical conductivity of the soil. Along with the EC, these measure soil moisture and soil temperature also. This measurement indirectly indicates the amount of soluble salts, and water present in the soil, and can serve as a valuable indicator of moisture and salinity stress level in the plat root zone.

Figure 1. Soil moisture, EC and temperature sensors for continuous measurement of profile soil water and salinity

Both soil moisture and EC sensors offer benefits for various applications, particularly in agriculture and environmental monitoring.

Enhanced Irrigation Efficiency: By accurately measuring soil moisture and salinity levels, these sensors help to determine the precise levels of water requirement of the crops. This prevents over irrigation and salt stress in the plant root zone and ensures optimal hydration for better growth and yield.

Reduced Water Waste: Precise irrigation leads to significant water savings and increase in water use efficiency.

Improved Crop Vigor: Optimal moisture levels and osmotic stress free condition contribute to healthier plants, leading to better crop vigor and yields.

Continuous Detection of Stress: Sensors continuously detect changes in salinity and moisture levels in soil than the traditional soil sampling methods and also help in continuous and early detection of moisture and salt stress. This allows for early intervention to prevent drought and osmotic stress in crops.

Data-Driven Decision Making: Sensor data provides valuable insights into soil moisture dynamics, enabling informed irrigation scheduling and other crop management practices.

Salinity Monitoring: EC sensors measure the electrical conductivity of the soil, which is an indicator of salt content. This helps to identify areas with high salinity levels that might be unsuitable for profitable cultivation of certain crops.

Soil Health Assessment: EC readings can be used as a general indicator of soil health, helping to identify potential problems like nutrient deficiencies or compaction.

Land Management: EC data can be valuable for land management decisions, such as selecting suitable crops for specific areas or identifying areas for remediation.

Both soil moisture and EC sensors are powerful tools that can revolutionize the way we manage soil and water resources. By utilizing their benefits, we can promote sustainable agriculture, improve crop quality and yields, and protect our environment for future generations.

Smart Tools for Large Scale Salinity Mapping

Electromagnetic Induction Techniques

Electromagnetic induction (EMI) is a geophysical technique that uses the principles of electromagnetism to measure the apparent electrical conductivity of soil profile (Narjary *et al.*, 2021). It is a powerful tool for measuring salinity, as electrical conductivity of a substance is directly related to its salt and water content. EM-38, EM-38MK2 and Dualem 421 are some of the most widely used EMI devices which are largely used in mapping and quantification of soil salinity at large scale.

Advantages of Using EMI for Salinity Measurement

i) **Non-Invasive:** No soil sampling is required, making it a quick and cost-effective method.

ii) **Rapid and Efficient:** Large areas can be covered quickly, providing high-resolution data.

iii) **Depth Penetration:** Different instruments can measure conductivity at various depths, depending on the frequency used (mostly 0-1.5 m depth)

iv) **Portable and Versatile:** Instruments are relatively lightweight and can be used in various terrains.

The EMI instrument (EM-38) works in both vertical and horizontal dipole modes and measures bulk soil salinity (apparent electrical conductivity, EC_a of a maximum of 1.5 and 0.75 m depth of investigation in vertical mode and horizontal mode, respectively.

Figure 2a. EM38 measurement in vertical mode

Figure 2b. EM38 measurement in horizontal mode

The device with a separate or integrated with GPS data logger records apparent conductivity (EC_a) of different depths with GPS point coordinates. A correlation equation for conversion of EC_a to soil salinity (EC_e) is required for the establishment of apparent to actual degree of salinity. These depth-wise salinity data with GPS coordinates are exported to ArcGIS software for data analysis which generates spatial salinity maps of different depths and mode using IDW/krigging methods. These maps help agency/farmers to understand and interpret yield variation with soil salinity in order to take corrective measures for improving crop yield.

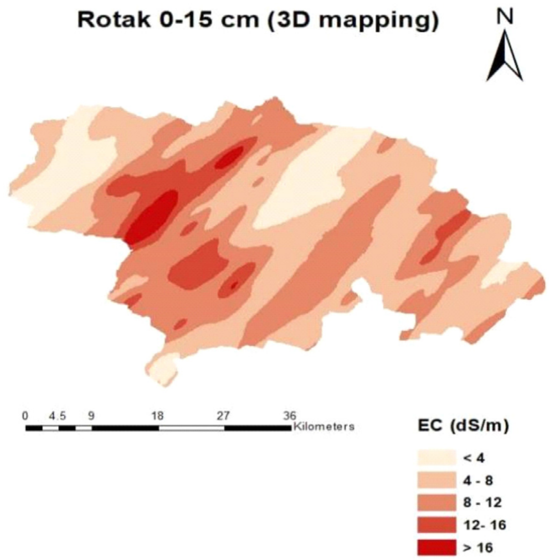

Figure 2c. Soil salinity map prepared using EMI techniques for Rohtak, District, Haryana

Factors affecting conductivity

- Amount of salts (ionic content, higher conductance)
- Clay content (higher clay content, higher conductance)
- Soil moisture content (higher ô, higher conductance)
- Compaction (higher compaction, higher conductance)
- Presence of soluble salts (Ca, Mg, K, Na) and exchangeable salts

Temperature: As temperature decreases to the freezing point of water, soil EC decreases slightly. Below freezing, soil pores become increasingly insulated from each other and overall soil EC declines rapidly.

The main advantage of geophysical instruments with multi transmitter and multi receiver is that they can properly describe depth wise distribution of soil salinity.

Remote Sensing: Satellite and aerial imagery can identify salt-affected areas, track changes over time, and help plan remediation strategies.

GIS Mapping: Combining sensor data with imagery allows for creating detailed maps of salt distribution, facilitating targeted interventions.

Advanced Irrigation Techniques

Precision Irrigation Systems: These systems deliver water based on real-time soil moisture data, minimizing water waste and preventing further salinization.

Drip Irrigation: Drip irrigation is an advanced method of pressurized irrigation system. This method delivers water directly to plant roots, reducing evaporation and salt accumulation near the surface. Drip irrigation enhances water application efficiency. It also provides many unique agronomic and water conservation benefits. Drip irrigation saves 50-70 % of applied water as compared to traditional flood irrigation system and also provide other benefits such as (i) fertilizer savings of up to 50 % (Jat *et al*., 2019) (ii) safer use of saline (Saxena *et al*., 2013) and wastewater (Tripathi *et al*., 2019) (iii) suitable for undulating and degraded land (v) prevents soil erosion (Abu-Hashim *et al*., 2021) (vi) increase yield and water use efficiency(Singh *et al*., 2009).

Over the two decades, drip irrigation systems extensively used on saline/sodic soil and found to improve crop output by driving salts towards the periphery of the wetting zone and lowering soil salts in the crop root zone (Guan *et al*. 2019). The global meta analysis finds that surface drip irrigation enhanced crop yield by 37.4% and reduced soil salinity in the root zone by 37.7% in comparison to conventional flooding irrigation (FI) (Du *et al*., 2023). In order to achieve sustainable soil health and agricultural production, drip emitters of 2–4 L h^{-1} discharge rate have been recommended for use of saline water (upto 2dS m^{-1}) irrigation at 50% crop evapotranspiration (ET_c) (Du *et al*., 2023).

Automated drip irrigation

Automated drip irrigation in saline and sodic soil is most efficient and smart technology for developing salt and moisture stress free environment in the crop root zone. In automated drip irrigation system, soil moisture and salinity sensors measured the real time salinity and moisture status in the field. Through micro controller system, the data are converted into electrical digital format, and by using radio frequency or IoT network, further transferred to the base station. When soil solution electrical conductivity exceeds tolerance limit and/or soil moisture drops below a critical moisture stress level, base station controller system activates signals to turn on the irrigation system. As the soil moisture and salinity level reaches to a pre-defined value, signal toes to the controller system and irrigation stops (Fig 3).

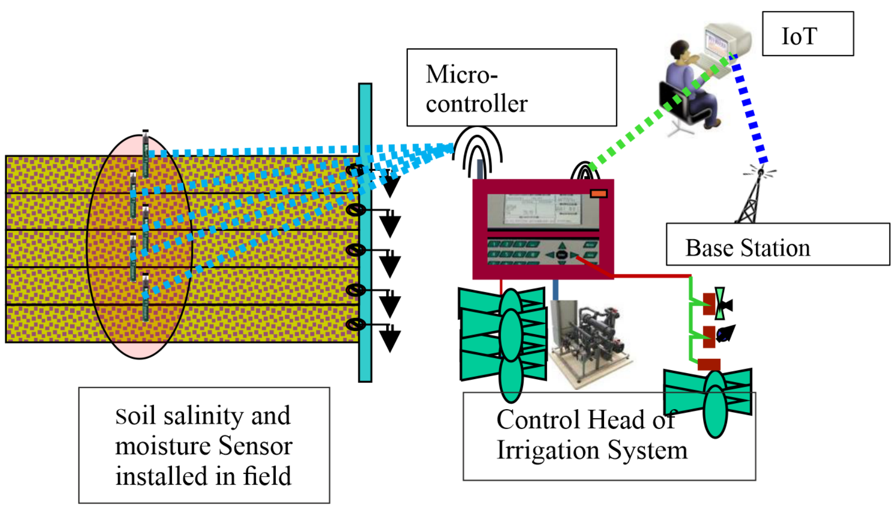

Figure 3. Automated drip irrigation system in saline environment

Studies on IoT based automated irrigation system in normal soil has gained pace in last decades but their performance needs to be validated in saline environments including use of saline water for irrigation. In normal soil condition at Ludhiana, Sidhu *et al*. (2019) developed magnetic soil tensiometer based automated sub-surface drip irrigation for rice-wheat cropping system under Conservation Agriculture (CA). They reported about 40–50% saving in irrigation water and 20% saving in nitrogen fertilizer under automated subsurface irrigation system as compared to traditional flood irrigated rice- wheat system. Kumar *et al*. (2023) evaluated soil moisture sensor and ET_c based smart drip irrigation system for sweet corn crop. They reported that the irrigation scheduling at 43.5% soil moisture (IoT-SM 43.5%) produce 12.05% higher yields with 11% water savings compared to 100 per cent- ET_c based irrigation system (IoT-ET_c). However, in saline conditions, there is need to determine crop wise salinity threshold for drip irrigation and its scheduling criteria (when and how much saline water should be applied for irrigation) in conjunction with moisture stress for precision agriculture using IoT in salt affected ecology.

Water and Salt Dynamics under Drip Irrigation System

In drip irrigation, salts distribution follows the pattern of soil moisture distribution and has the tendency to accumulate at the periphery of the wetted soil mass (Fig. 4). In wetted zone, below the dripper, most of the roots are concentrated in the wetted soil profile and function with low to medium salinity values depending upon the irrigation water salinity. The accumulation of salt is greater in upper soil layer than the deeper layers due to upward flux to meet evaporative demand and increases with distance from the dripper. However, frequent watering under drip irrigation maintains relatively higher soil moisture than conventional irrigation methods and minimizes the adverse effect of matric and osmotic stress on plant growth (Dong *et al.*, 2021). The saline water irrigation may cause a salinity build-up in the area of low annual rainfall (< 250 mm) and might become a problem for plant growth (Phocaides, 2007). To avoid this situation, leaching of salt beyond the root zone is recommended, particularly at the end of the season, once in a year.

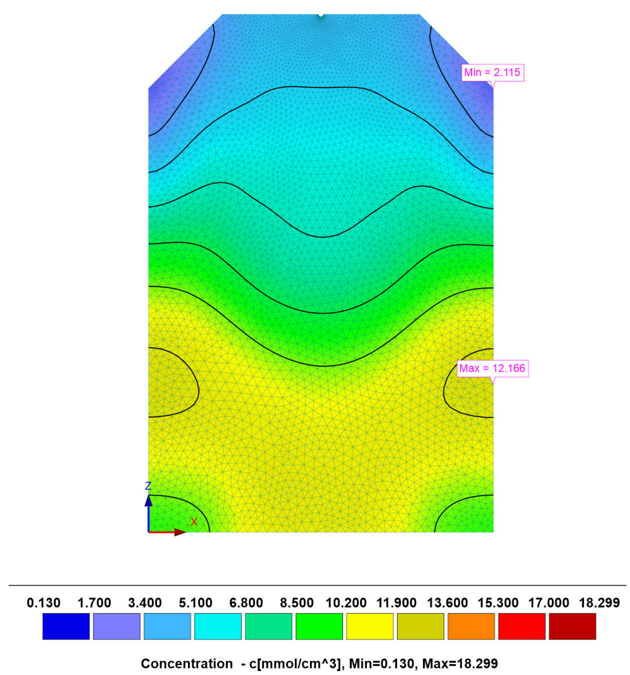

Figure 4. Salt distribution in drip irrigated system

Drainage Systems: Efficient drainage system helps in removing excess salts and free water from the soil, and improving soil health. This can be achieved through controlled drainage system. In a controlled drainage system, a control structure keeps the water table at a reduced but desired depth by limiting its subsurface drainage flow and raising possible capillary upward flow due to evaporative demands (Fig 5). In most of the cases, controlled structures (valve that can be opened or closed to control the flow of groundwater water out of the pipe drainage system) are installed at the end of lateral subsurface drainage pipes. This allows for the storage of water in the soil profile during the dry periods when drainage is not needed. Compared to the uncontrolled system, the flow lines are shallower and more concentrated towards the surface of soil. The provision of water flow controlling devices in the drainage channels, which may be operated as and when necessary, can be used to manage the controlled drainage at various water table depths to satisfy the irrigation needs of various crops. In addition, it saves irrigation amount and nutrient losses as compared to excess drainage in conventional subsurface drainage system. Working in a saline Vertisols region of Tungabhadra canal command area of Karnataka, India, Karegoudar *et al*. (2019) reported that controlled drainage resulted in a 64% decrease in drain discharge volume compared to conventional subsurface drainage and also resulted in 17% irrigation water savings. Average nitrogen loss was reduced by 50.4% under controlled drainage system compared to conventional SSD. The reduced drain flows and lower salinity result in much reduced salt load and comparable grain yield in control SSD compared to conventional SSD system.

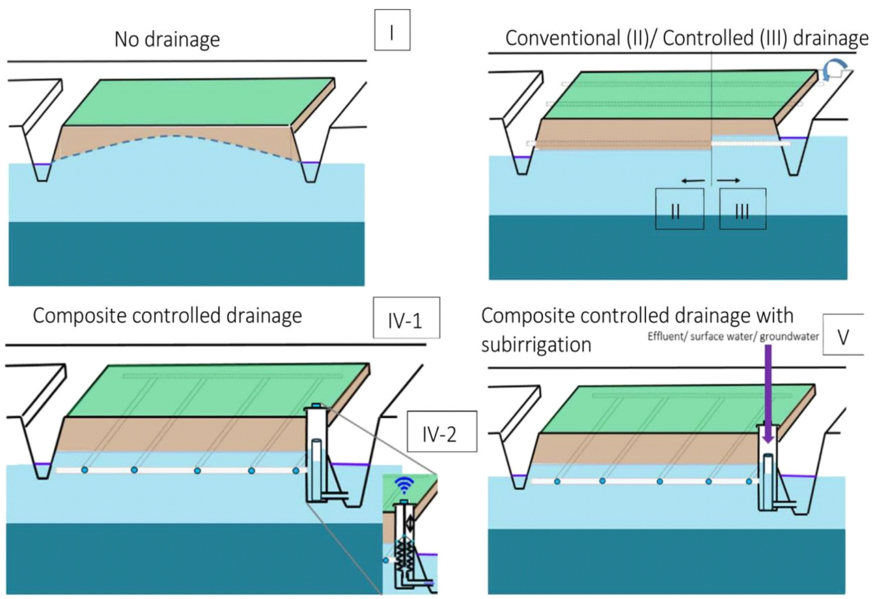

Figure 5. Control drainage system

Cut-soiler Constructed Preferential Sub-surface Drainage (PSSD)

Cut-soiler is a tractor mounted machine which constructs shallow sub-surface drainage by using surface crop residue. Cut-soiler machine cuts the soil and opens V-shape furrow by lifting the cut soil and fills it back by placing the surface scattered filling material such as straw and residue at bottom followed by overlaying the lifted soil (Fig. 6). Salt moves through preferential flow lines and removed from the system by constructed shallow sub-surface drain when irrigation is applied or rain takes place. Cut-soiler PSSD is found very much effective in controlling sub-surface soil sodicity and dry land soil salinity in areas where groundwater table is relatively deeper. In order to address the sub-surface soil sodicity and surface waterlogging in heavy texture soil, ICAR-Central Soil Salinity Research Institute in association with Japan International Research Center for Agricultural Sciences (JIRCAS) has conducted studies on farmers' fields. Studies compared the effects of placing gypsum and rice residue by Cut-soiler at various lateral intervals to assess improvement in crop yield and mitigation of sub-surface soil sodicity at Budhmor (Patiala) Punjab. The Cut-soiler machine

Figure 6. Cut-soiler machine and its operation to construct preferential flow path for control salinity and subsoil sodicity

was operated at 2.5, 5.0, and 10.0 m lateral spacing for the sub-surface application of gypsum, rice residue, and gypsum + rice residue at 0.4 m depth. Results revealed that sub-surface soil sodicity (ESP) was decreased by ~24, 15, and 6% at lateral distances of 0.30, 0.60, and 1.25 meters, respectively. There was an increase in the grain and biological yield of rice and wheat at 2.5 m spacing of Cut-soiler PSSD than 5 and 10 m spacing (Yadav *et al*., 2022).

For managing soil salinity where groundwater table depth remains below the root zone, Cut-soiler PSSD was constructed with rice residue placement at 2.5m, 5 m 7.65 and 10 m spacing at ICAR-CSSRI research farm, Nain (Panipat), Haryana. Pearl-millet- mustard cropping system was practiced in this study. Soil salinity and moisture were monitored through soil salinity and moisture sensors (GS3 Greenhouse Sensor, METER Inc) for three years (2018-21). Results revealed that the Cut-soiler PSSD was very much effective in reducing soil salinity from the root zone. Pore water electrical conductivity (EC_p) of the soil in the plots with 2.5 and 7.5 m spacing was lower than that of the soil without Cut-soiler PSSD. Consequently, it also increased pearl-millet and mustard yield than that of without drainage (Anzai *et al*., 2022)

6. Digital Platforms and Decision Support Systems

Digital platforms and decision support systems (DSS) are designed to assist farmers in managing salt affected soils. These tools provide valuable information and insights about type and degree of land degradation, suitable management practices, suitable crops, irrigation requirements, fertilization, extent of yield loss due to salinity and other cropping practices.

Digital Platforms

Digital platforms provide access to a variety of data and resources related to saline soil management to farmers. Some of the most common features of digital platforms are:

Soil Maps: These maps show the distribution of salinity across a field or region. (https://cssri.res.in/extent-and-distribution-of-salt-affected-soils-in-india/)

Weather Data: This data can be used to predict future irrigation needs and to avoid salinization caused by over-irrigation. (https://cssri.res.in/)

Crop Models: These models can be used to simulate the effects of different management practices on crop yields.

Expert Advice: Farmers can connect with experts through digital platforms to get advice on saline soil management.

Decision Support Systems

DSS are computer programs that can help farmers make decisions about saline soil management. These systems use data from digital platforms to generate recommendations for irrigation, fertilization, and other cropping practices. Some of the benefits of using DSS include:

Improved Decision Making: DSS can help farmers make more informed decisions about saline soil management that lead to improved crop yields.

Reduced Costs: DSS can help farmers save money by optimizing their use of water and fertilizer.

Increased Sustainability: DSS can help farmers to manage saline soils in a more sustainable way.

ICAR-CSSRI has also developed an ICT-based mobile App "Salinity Expert' (Fig. 7) for dissemination of salinity management technologies to the farmers of salt affected soil (Sheoran *et al.*, 2018). This DSS mobile App was developed in farmers' friendly Hindi language. This App contains knowledge based digital compendium including management practices for rice, wheat and mustard crops under salty environments right from sowing to harvesting. It also provides information on estimated gypsum requirement considering inherent soil sodicity (pH) and residual alkalinity in irrigation water (RSC) and their concomitant effect on crop yields (yield predictions). It also provides agro-advisories and information pertaining to training programmes, methodology and precautionary measures while taking soil and irrigation water samples and other important events. This App has inbuilt system of expert-user interaction system. It includes user friendly query handler to raise queries either as text messages or in graphic/recorded form. The App administrator attends raised queries via message sorting, short message service, email etc.

Figure 7. Salinity Expert-Mobile App based decision support system in saline environment

Conclusion

Overall, smart tools offer promising solutions for managing salt-affected soils. By adopting these technologies and adapting them to local conditions, farmers can improve soil health, enhance crop productivity, and contribute to sustainable agricultural practices.

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Digital Tools in Integrated Farming Systems: Revolutionizing Agriculture through Smart Technologies

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Introduction

Providing food has become more complex because of climate change and other environmental and societal stressors, such as political instability, the growth in the world population, and outbreaks of new diseases. Integrated Farming Systems (IFS) represent a holistic approach to agriculture, aiming to maximize efficiency, sustainability, and productivity. This approach involves the integration of different agricultural activities such as crop cultivation, livestock farming, poultry, aquaculture, and agroforestry. In response to the challenges, the agri-food industry has increased its efforts to shift to using more digital tools and other advanced technologies (Housson *et al.*, 2023). In recent years, the agriculture sector has witnessed a significant transformation with the incorporation of smart technologies and digital tools into Integrated Farming Systems. This integration has not only addressed longstanding challenges faced by farmers but has also paved the way for a more sustainable and resilient agricultural future. Digitalization may cause the next agricultural revolution as it has a unique potential to make crop and livestock production more efficient and environmentally friendly, thereby creating substantial benefits for farmers, consumers, and society at large (Basso & Antle, 2020).

The Need for Digital Transformation in Agriculture

Traditional farming practices often face challenges related to resource optimization, climate change impacts, and market fluctuations. Integrated Farming Systems emerged as a response to these challenges, promoting diversification and synergy among different farming components. However, the adoption of digital tools has taken this concept to new heights, offering farmers unprecedented control and insights into their operations. Some of the key enablers of the digital transformation are smart farming technologies, artificial intelligence, robotics, smart sensors, IoT (Internet of Things) etc (Fig. 1.) for which mobile phone and internet services are most common gateway.

As the world is welcoming its 8 billionth inhabitant, 5.3 billion people – or 66 per cent of the total global population – are online (ITU, 2022). The global growth mobile ownership and internet usage by both rural and urban population aids in this journey of digital transformation. Since mobile phones are the most common gateway to the Internet, the percentage of individuals owning a mobile phone is a good indication of Internet penetration. Data show that, globally, 73 per cent of the population aged 10 and over own a mobile phone in 2022, seven percentage points higher than the percentage of individuals who use the Internet (Fig 2.). This gap is closing in all regions, as growth

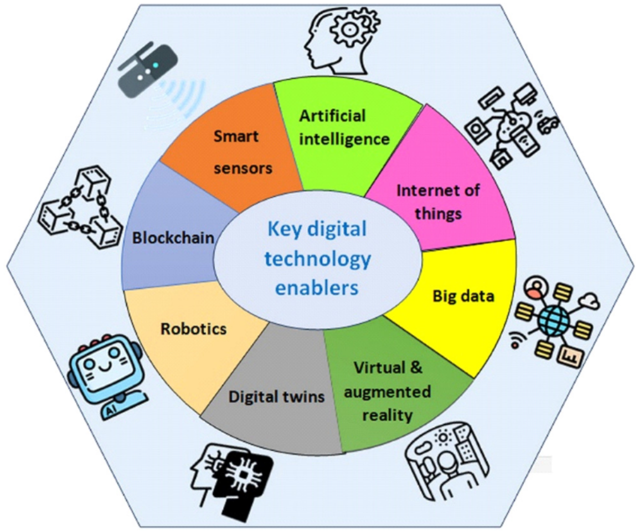

Figure 1. Key enablers of digital transformation (*Source:* Housson *et al.*, 2023)

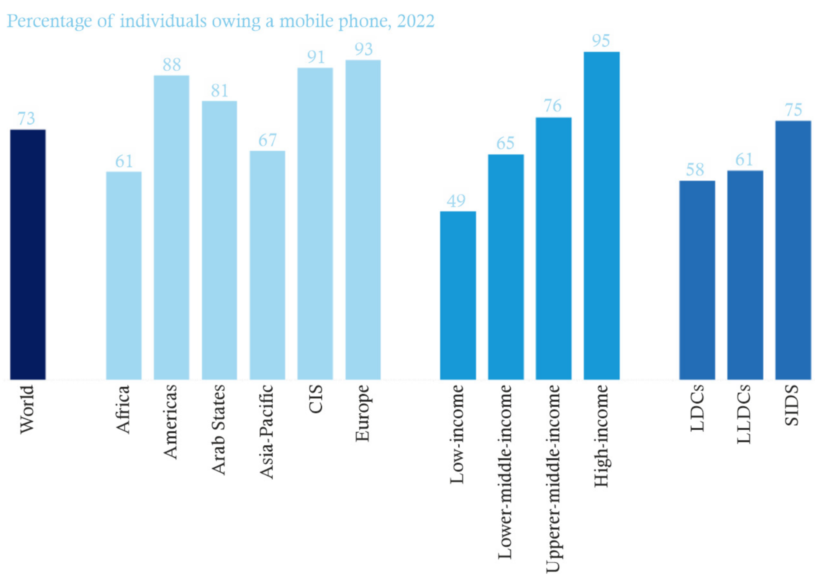

Figure 2. Global Ownership of Mobile Phones (*Source:* ITU, 2022)

in Internet use has significantly outpaced the growth of mobile phone ownership over the last three years.

Three-quarters of 15- to 24-year-olds use the Internet. Worldwide, 82 per cent of urban dwellers are using the Internet in 2022. That percentage is 1.8 times as high as the percentage of Internet users in rural areas. Over the last three years, the ratio has decreased from 2.3 to 1.8, as rural areas gradually catch up. In the Asia-Pacific region, the ratio is 1.8, down from 2.4 three years ago. This calls for tapping the potential of this digital revolution for transforming the agri-food system to tackle the challenges in changing climatic scenario.

Smart Technologies in Farming Systems

India, with its diverse agro-climatic zones and a significant agricultural workforce, stands to benefit immensely from the application of digital tools in farming systems. Several digital tools and technologies have been introduced and adopted in the country, addressing various challenges faced by farmers. There are various modes- push and pull SMS, interactive voice response, mobile apps, and so on- through which mExtension services are provided either individually or in combination. While SMS and interactive voice response services are accessible from both conventional and smart phones, mobile apps require smart phones. Services can be free or subscription-based. Communication tools, info graphics, video, specific social media tools. Farm Software, web and phone application, Digital education and training materials and supports, Digital sensors and data collection and analysis, decision support tools, Digital marketing support tools. Benefits of incorporating digital technologies in agriculture are manyfold (Fig. 3).

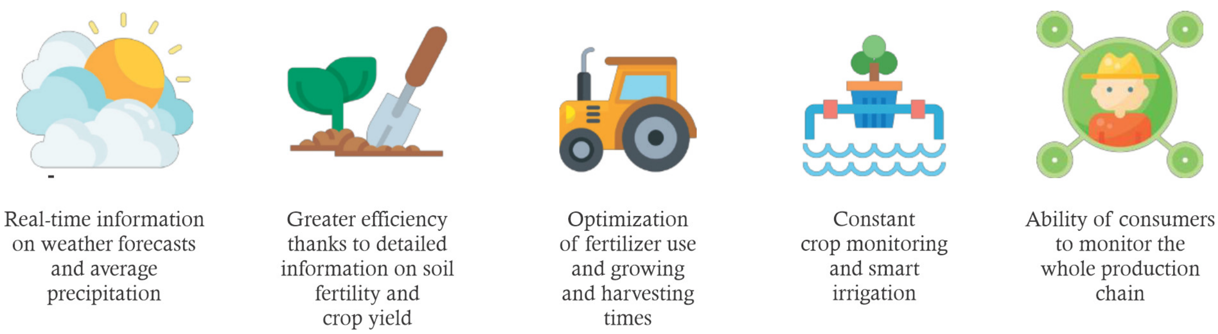

Figure 3. Smart agriculture: the benefits of incorporating digital technologies into agriculture (*Source:* Economic Commission for Latin America and the Caribbean (ECLAC, 2020))

The application of these tools in Indian farming systems can be categorized into several key areas:

Precision Agriculture

Precision agriculture technologies are being increasingly used in India to optimize resource use and enhance crop yields. Precision farming uses modern technologies such as satellite imagery or

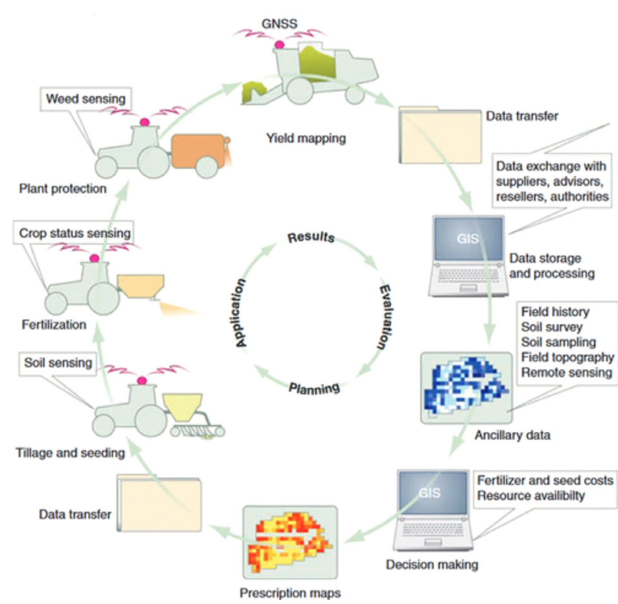

Figure 4. Precision farming information flow in crop production
***Source:* Gebbers & Adamchuk (2010, p. 830)**

field mapping to improve crop quality and profitability. Moreover, it optimizes the use of traditional resources. Therefore, this agricultural management system contributes to the development of sustainable agriculture, allowing to solve both economic and ecological problems, which are becoming more acute. Among the technologies used in such a system are GPS, drones, and satellite images. Based on this data, farmers receive information on all key issues: crop status, weather forecasts, environmental changes, etc. Also, the important difference between precision farming and traditional agriculture is the ability to manage fields not as a single block but by dividing them into separate areas. These tools help in precise planting, fertilization, irrigation, and pest control, ensuring efficient use of resources and minimizing environmental impact. Precision farming involves the use of technology to optimize field-level management with regard to crop farming. This technology enables precise application of fertilizers, pesticides, and water, reducing waste and environmental impact while improving overall yield. Companies like CropIn and Agribolo offer precision agriculture solutions that provide real-time monitoring and data analytics for better decision-making.

Soil Health Monitoring

Digital tools for soil health monitoring play a crucial role in Indian agriculture. Soil sensors and testing kits are used to assess soil fertility, moisture levels, and nutrient content. By understanding the soil conditions, farmers can make informed decisions about fertilizer application and crop selection. The Soil Health Card scheme by the Indian government promotes the use of digital tools to assess and manage soil health. Soil health card portal uses seamless integration with GIS system so that all the test results are captured and can be seed on map. QR code based soil sample collection app developed by Ministry of Agriculture and Farmers Welfare as a reference app which can be directly used by state govts.

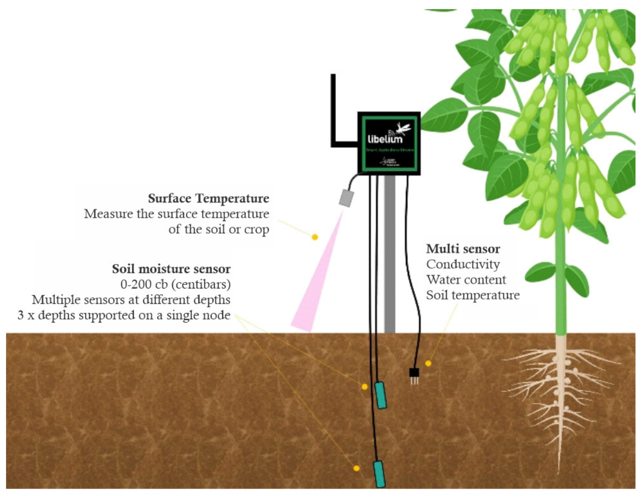

Figure 5. Soil Health monitoring using IoT

Weather Forecasting and Advisory Services for Climate Resilience:

Risk is an important aspect of the farming. The uncertainties inherent in weather, yields, prices and other factors that impact farming can cause wide swings in farm income. The agricultural sector is exposed to a variety of risks which occur with high frequency. These include climate and weather risks, natural catastrophes pest and diseases, which cause highly variable production outcomes. Given the dependency of agriculture on weather conditions, accurate and timely weather information is crucial for farmers. Numerous mobile apps and services provide real-time weather updates and forecasts. The Indian Meteorological Department (IMD) offers services like Agro-Met Advisory, providing location-specific agricultural advisories based on weather conditions. Digital innovations, such as open satellite data, low-cost sensors, big data and machine learning, have been key enablers of digital climate resilience services. Mobile network operator (MNO) assets provide the basis for further innovation, facilitating localisation and scale-up of these services.

Internet of Things (IoT) in Livestock Farming

Incorporating IoT devices into livestock farming has proven to be a game-changer. Smart collars for cattle, for example, can monitor the health and behavior of animals in real-time. This not only helps in early detection of diseases but also aids in optimizing feeding schedules, reducing veterinary costs, and improving overall animal welfare.

Automated Aquaculture Systems

In aquaculture, the integration of digital tools has led to the development of automated systems that monitor water quality, feed fish based on their growth rates, and even harvest fish at optimal times. These systems enhance efficiency and sustainability in aquaculture, addressing concerns such as overfeeding and water contamination.

Agroforestry Apps for Sustainable Land Management

Digital tools have facilitated the implementation of agroforestry practices by providing farmers with apps that assist in planning and managing mixed-crop and tree systems. These apps consider factors such as climate, soil type, and market demand, helping farmers make informed decisions about which crops and trees to plant, ultimately promoting sustainable land use.

Farm Management Software

Farm management software is gaining popularity among Indian farmers for its ability to streamline various farm operations. These software platforms assist in crop planning, inventory management, financial tracking, and market information. Examples include FarmERP and FarmLogs, which offer comprehensive solutions for farm management, improving efficiency and decision-making.

E-Marketplaces and Agri-Tech Startups

Digital platforms and agri-tech startups are connecting farmers directly with buyers, reducing the dependency on traditional intermediaries. Companies like AgriBazaar and Ninjacart facilitate online trading of agricultural produce, enabling farmers to access wider markets and get better prices for their crops.

Mobile Apps for Agricultural Extension

Mobile applications are being used for agricultural extension services, providing farmers with access to information and knowledge. Apps like mKisan and Plantix offer features such as crop advisories, pest and disease identification, and market prices. These apps empower farmers with real-time information, helping them make informed decisions. Some useful mobile apps for farmers are listed below:

Mobile Apps: . Kissan Suvidha 2. Kheti Badi 3. IFFCO KISAN. 4. FERTILIZER CALCULATOR 5. Agri-market mobile app 6. Mandi Trades 7. Mausam 8. DAMINI: Lightning Alert 9. MEGHDOOT 10. YouTube for the farm

Voice Call Based Advisory Tools: 1. Kissan call center 2. Krishi Vani Website Based Advisory Tools: 1. E-CHOUPAL 2. e-NAM (National Agriculture Market) Television Based Advisory Tools: DD Kisan

Drones in Agriculture

Drones equipped with cameras and sensors are employed for crop monitoring and surveillance. In India, drones are used for assessing crop health, identifying pest infestations, and monitoring large agricultural areas after policy relaxation by Govt of India. This technology aids farmers in taking preventive measures and optimizing resource use. This emerging technology can help reduce time and increase the efficiencies of the farmers. The use of drones in the agricultural sector is only expected to rise as the industry matures.

Government Initiatives

The Indian government has launched various initiatives to promote the use of digital tools in agriculture. The Pradhan Mantri Fasal Bima Yojana (PMFBY) leverages technology for crop insurance, the National Agricultural Market (e-NAM) facilitates online trading of agricultural commodities and kisan drone scheme with subsidy for drone for promotion of drone application in agriculture. These initiatives aim to enhance transparency, reduce inefficiencies, and improve the overall agricultural ecosystem.

Figure 6. Application of Drones for spraying and crop health monitoring

Challenges and the Way Forward

While the benefits of incorporating digital tools into Integrated Farming Systems are evident, challenges remain.. Farmers often face issues related to initial costs, technological literacy, and reliable access to digital infrastructure. Addressing these challenges requires concerted efforts from the government, private sector, and non-governmental organizations. However, the long-term benefits, including increased productivity, reduced resource usage, and improved resilience to climate change, make the adoption of these technologies a worthwhile investment. Investments in digital infrastructure, farmer education programs, and policy support for the adoption of emerging technologies will be crucial to realizing the full potential of digital tools in Indian farming systems. As the digital landscape continues to evolve, India's agriculture sector is poised for a transformative journey towards sustainability, efficiency, and increased farmer prosperity. Ingram and Maye (2020) opined that new data driven processes on farm, as well as the changing Agricultural Knowledge Information System (AKIS) dynamic under digital agriculture, bring new demands, relations and tensions to agricultural decision-making, but also create opportunities to foster new learning by harnessing synergies in the AKIS.

Conclusion

The integration of digital tools into Integrated Farming Systems marks a significant step towards a more sustainable and efficient agricultural future. Digital tools play a crucial role in disseminating information to farmers enabling them to decide on the cropping pattern, use of high yielding seeds, fertilizer application, pest management, marketing, etc. With IoT, farming has become data-driven, enabling timely, cost-effective, and ecologically sustainable farm management. Thus, developing countries whose GDP depends on farming must include IoT in farming (Sharma *et al.*, 2023). Digital advisory is a potential tool for improving decision making in agriculture. In the last few decades, information and communication technologies (ICTs) have provided immense opportunities for the social and economic development of rural people. Precision farming, IoT in livestock, automated aquaculture systems, and agroforestry apps are just a few examples of how smart technologies are revolutionizing farming practices. As these technologies become more accessible and affordable, the agriculture sector is poised for a transformation that not only addresses current challenges but also prepares for the uncertainties of the future. This digital revolution in agriculture is very promising and will enable the agriculture sector to move to the next level of farm productivity and profitability. This transformation process looks irreversible and poised to revolutionize not only agriculture but the entire farm-to-food sector (Himesh *et al*., 2018). Embracing digital tools in Integrated Farming Systems is not merely a choice but a necessity for ensuring food security, environmental sustainability, and the economic well-being of farmers worldwide.

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Role of Smart Technologies in Plant Nutrient Recommendations for Better Crop and Soil Health Management

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A sustainable climate resilient cereal-based crop production system is of utmost demand/ need to address the challenges of food and nutritional security *vis-à-vis* the proclamation of 'zero hunger' by 2030 (SDG2) of the United Nation in a holistic manner. Smart technologies play a crucial role in revolutionizing plant nutrient recommendations for better crop and soil health management. By leveraging advanced sensors, data analytics, and artificial intelligence, these technologies can provide location specific precise recommendations tailored to the specific needs of each field or crop. One of the key advantages of smart technologies is their ability to collect real-time data on crucial factors like soil nutrient levels, moisture content, and plant health. This data is then analyzed to generate accurate plant nutrient recommendations, ensuring that crops receive the right amounts of nutrients at the right time. Thus farmers can optimize nutrient uptake by avoiding over- or under-fertilization, minimize waste, and reduce environmental impact. Moreover, smart technologies enable farmers to monitor and manage their fields remotely, saving time and effort. With the help of connected devices and mobile applications, farmers can receive alerts and insights about their crops' nutrient requirements, allowing them to make timely adjustments and interventions.

Sampling strategy

Sampling is the first step of soil fertility evaluation, mapping and soil health card generation. These activities can be used for deciding nutrient management for precision agriculture and to arrive at decisions on plant nutrient management strategy of the area. Also such maps may be used for soil quality assessment over a period of time by periodical assessment from same GPS points to ascertain whether the soil quality is sustaining or aggrading or degrading. Sekhon *et al*. (2017) have developed a new method for computing reliable sample size for prescribing soil test based nutrient management interventions. In addition, we need to have better tools for tracing the soil samples collected for SHC Scheme with precise GPS tagged for better delivery of quality recommendation and pin-pointing/correcting sources of error (Dey, 2019).

Grid sampling is an unbiased and relatively quick method of obtaining soil samples and generating location specific soil management recommendations. There are softwares to facilitate it. After the samples have been pulled from georeferenced sites and analysed, a map is made by either filling in the grid cells with the soil test value (grid cell method) or assigning the soil test value to a point and then interpolating between points (grid point method). Grid sampling results in either a 'checkerboard' map (grid cell method) or a 'smoothed' map (grid point method). The ultimate aim is to prepare maps for deciding on management strategies regarding assessment of plant nutrient status, diagnose suspected nutrient imbalances, monitor effects of management on crop nutrient status and soil fertility, assess availability of toxic elements and provide basis for making plant nutrient recommendations for increasing crop yield and improving quality, improving nutrient use efficiency, decreasing impacts on water quality and improving soil quality. However, there are shortcomings in this approach too. The glitches include the absence of unanimity on appropriate grid size and mode of determining the same. Also there are instances of unduly biased results by localized irregularities of maps prepared from grid samples. Further uniform grids are susceptible to systematic errors and result in both under/over sampling if soil regions vary in size. There is also the danger of grid cell sampling results in cells being averaged over dissimilar soil types. Unfortunately, the localized irregularities are encountered more often than not under field condition. Farmers are more aware of such irregularities in their respective fields. Hence, the participatory sampling process has enough scope for scaling up in other regions. The deficiencies can be minimized by adoption of appropriate sampling and intensity of management through directed sampling. The realization of the fact that involving farmers, the major stakeholder in any agri-based project, is the key for faster adoption and implementation of technology, a directed sampling process has been followed in the GIZ-NABARD ProSoil project of Mandla and Balaghat with strong participation of the community (ProSoil Newsletter, 2018). In the process, it was possible to integrate the experience and wisdom people about their soils, parcel of land, productivity, etc. with scientific knowledge to arrive at a robust approach. The farmers' experiences not only lead to more knowledge but also more fine tuning of the maps with their understanding of yields, topography, water retention capacity and soil health management history. It was thus possible to make appropriate cluster for developing soil fertility maps with their understanding of their own lands. The added advantage of participatory directed sampling process is that it captures localized irregularities better and hence, the decision arrived at from this process is superior.

Automation in sampling

Soil sampling is the stepping stone for evaluating soil fertility and making strategic decisions on plant nutrient application. Soil analysis and plant nutrient recommendation depend on the small amount of sample collected. The COVID-19 pandemic called for paradigm shift towards current method of sampling which is human power intensive with chances of infection (Dey and Bhattacharyya, 2021). Automation will help in this endeavour. Hydraulic electro-mechanical devices using cloud based control software were found to be faster than traditional method. Articulated steering of autonomously navigating unmanned ground vehicle platform prototype with soil sampling mechanism has already been developed (Valjaots *et al.*, 2018), where intervention of operator is minimised only to the process planning, robot transportation and handling of collected samples. Implementation of mobile technology for soil sampling automation has significantly increasing the efficiency of the process. This automated and remotely controlled technology will also help in more frequent sample collection than traditional human operated manual methods. Purdue University also developed autonomous high-speed robot with self-cleaning hydraulic auger, named 'Smartcore', which collects accurate, repeatable soil samples. In addition, drones can be employed to produce precise 3-D maps at the start of crop cycle for deciding the basal application of plant nutrients as well as planting. During standing crops, it may be employed to arrive at decision on irrigation and nitrogen management. However, the drone-aided soil mapping procedure has to be simple and easy to adopt.

Use of GPS/GIS-based soil fertility mapping for development of cusmomised fertilizers

The concept of balanced use of fertilizers to promote site specific nutrient management can be achieved through customised fertilizers. The customized fertilizer formulations can be derived from basic data of STCR and clustering of response zones through GPS/GIS-based fertility mapping helped in encouraging the balanced use of fertilizer application, better nutrient use efficiency and higher profit in the hands of farmers. The steps involved to arrive at customized grades are, (i) geo-referencing of chosen area, (ii) selecting sampling points based on appropriate statistical procedure, (iii) actual sampling of the sites, (iv) analyzing soil, plant and water samples for nutrients and some soil characteristics, (v) development of customised soil fertility maps using GIS, (vi) defining management zones, (vii) yield targeting in major management zones, (viii) computing crop removal of nutrients, (ix) calculating nutrient requirement (amount and ratio), (x) blending of nutrients based on the generated information, and finally (xi) minor adjustment for physical stability of customised grades. GPS/GIS-based soil fertility maps of both macro- and micro-nutrients developed for 173 districts of India by ICAR-IISS, Bhopal in collaboration with mainly AICRP (STCR) centres (Basavaraja *et al*., 2016, 2017; Chitdeshwari *et al*., 2017; Dey *et al*., 2017a; Maragatham *et al*., 2014; Mishra *et al*., 2015, 2016, 2017; Santhi *et al*., 2018; Sellamuthu *et al*., 2015; Sethy *et al*. 2019; Singh *et al*., 2015, 2016) were used for the purpose. The per cent contribution from soil and fertilizers were determined by using AICRP on Soil Test Crop Response (STCR) data-base and applied for respective crop. This value was then corrected for nutrient available from the soil and for the fertilizer nutrient utilization efficiency (determined by using STCR equation) by the respective crop. The secondary and micronutrients were included in the above derived grade through nutrient indexing method and prevalent deficiency.

The technology developed has been adopted by Indo Gulf Fertilisers, Jasdishpur, Coromandal Fertilisers and NFCL, Hyderabad. For example, the customized grades were finalized in a consultancy project under PPP mode with M/s. IndoGulf Fertilisers, Jasdishpur. It was observed that Sulfur, Zinc and Boron were deficient in the soils of these districts. Based on this observation, the micronutrient Zinc, Boron and secondary nutrient Sulphar were included in NPK derived values to arrive at following customized fertilizer formulations: For Maize, NPKSZnB 14:22:12:05:0.5:0.05 in cluster of districts, viz., Purnia, Kathiar, Araria, Kisanganj, Siwan and Saran; NPKSZnB 11:21:16:05:0.5:0.05 in cluster of districts, viz., for Muzafarpur, Vaishali, Madehpura, Saharsa and Supaul of Bihar. For potato, NPKSZnB 12:16:18:06:0.6:0.1 05 in cluster of districts, viz., Mursidabad, Malda, Nadia, Bankura, Birbhum and West Midnapur; NPKSZnB 12:16:22:06:0.6:0.1 in cluster of districts, viz., Howarh and North 24 Parganas of West Bengal. Besides, Nagarjuna Fertilisers and Coromandal International have also used above methodology for deciding on customised fertilizer formulations. These customized were included under Fertiliser Control Order.

Use of soil fertility mapping for interpolation: a case study from Madhya Pradesh

The selection of best interpolation technique to assess soil physico-chemical properties of any unsampled location is very important. It is critical to choose the optimum interpolation technique for assessing soil physico-chemical parameters in any unsampled area for use in plant nutrient decision. A Case Study was undertaken for eastern part of Madhya Pradesh to determine the suitable interpolation technique for mapping soil properties, the inverse distance weighting (IDW), ordinary kriging (OK), and spline were compare and analyze (Kanwaria *et al*., 2021). Relationships between the statistical properties of the data were analyzed using soil test of pH, electric conductivity, organic carbon, nitrogen, phosphorus, potassium, sulfur, and zinc, from 2150 different locations (0–15 cm). For inverse distance weighting and spline, we used exponent value of 1, 2, and 3, and these values were decided from the RMSE value. The ranges of 5–30 closest neighboring points were selected for interpolation methods. Out of total 2150 samples, 10% points were preserved for validation using root mean square error (RMSE) test. Overall, all of the methods gave similar RMSE values. On this study, ordinary kriging (exponential) performed well for pH, K, and S, whereas IDW best for OC, N, and P while spline for EC and Zn. In all uses of IDW, the power of one was the best choice; it is possibly due to the low skewness in OC, N, and P. In all circumstances, a significance of three was established to be the best control for splines. Lognormal kriging gave better result where coefficient of skewness larger than one. It was concluded that many parameters can be better ascertained from the RMSE value obtained from validation.

On-line fertilizer recommendation systems - DSS

DSSIFER

Decision Support System for Integrated Fertiliser Recommendation (DSSIFER) is a user friendly software and the updated version (DSSIFER 2010) encompasses soil test and target based fertiliser recommendations through Integrated Plant Nutrition System developed by the AICRP-STCR, Department of Soil Science and Agricultural Chemistry, TNAU (Dey, 2016). STCR recommendations are not available for a particular soil–crop situation, the software can generate prescriptions using blanket recommendations based on soil test values. Using this software, fertilizers doses can be prescribed for about 1645 situations and for 190 agricultural and horticultural crops along with fertilisation schedule. If site specific soil test values are not available, data base included in the software on village fertility indices of all the districts of Tamil Nadu will generate soil test based fertiliser recommendation. Besides, farmers' resource based fertilizer prescriptions can also be computed. Therefore, adoption of this technology will not only ensure site specific balanced fertilisation to achieve targeted yield of crops but also result in higher response ratio besides sustaining soil fertility. In addition, the software also provides technology for problem soil management and irrigation water quality appraisal. Moreover, STLs of all the organisations can generate and issue the analytical report and recommendations in the form of Soil Health Card (both in English and Tamil) which can be maintained by the farmers over long run.

Nutrient Expert

Developed by International Plant Nutrition Institute and its partners, *Nutrient Expert®* is a tool that is based on the plant-based approach of SSNM (Dey, 2016). It utilizes information provided by a farmer or a local expert to suggest a meaningful yield goal for his location and formulates a fertilizer management strategy required to attain the yield goal. The required information about the production system is gathered through a set of simple, easily answerable questions that analyses the current nutrient management practices and develops guidelines on fertilizer management that are tailored for a particular location, cropping system and considers the organic inputs as a part of the system nutrient balance.

http://www.soilhealth.dac.gov.in

STCR prescription equations were included in the soil health card portal developed by Department of Agriculture, Cooperation & Farmers Welfare, Ministry of Agriculture & Farmers

Welfare, Govt. of India (Dey, 2016). This is a single, generic, uniform, web based software which can be accessed at the URL www.soilhealth.dac.gov.in, with facilities for registration of soil samples, recording test results of soil samples and generation of Soil Health Card (SHC) along with Fertilizer Recommendations. It is a workflow based application with following major modules: (i) Soil Samples Registration, (ii) Test Result Entry by Soil Testing Labs, (iii) Fertilizer Recommendations, (iv) Soil Health Card generation along with Fertilizer Recommendation and amendment suggestions, and (v) MIS module for monitoring progress. It promotes uniform adoptions of codes, e.g., Census Codes for locations. The system has sample tracking feature and will provide alerts to farmers about sample registration and generation of Soil Health Card through SMS and Email. Based on test results, these recommendations will be calculated automatically by the system. The System envisaged creating a unified national database on soil health that can be used for planning and research in the future.

Soil spectroscopy for rapid evaluation of soil fertility

In the backdrop of COVID-19 pandemic, non-contact/ minimum-contact soil testing methodologies has assume greater significance (Dey and Bhattacharyya, 2021). Further, with increasing costs for fertilizer inputs, farmers are interested in applying plant nutrients precisely for optimal profit. This warrants for precise methods of soil testing. Additionally, environmental concerns continue because a large amount of plant nutrient from agricultural fields moves into streams, rivers and the ocean, causing eutrophication. Since farmers apply more nitrogenous fertilizer, multidisciplinary approaches involving soil science, engineering and information technology will be emphasized for exploring new technologies for improved N management. In this context, light reflectance sensors for determining the most profitable N rates in different crops will be worthy. IT-based soil testing technology will not only save testing time but will also generate large number of soil test reports in minimum possible time without any chance of error. Furthermore, it will be helpful the STLs to achieve their target. Another way forward will be development of universal extractant/method and its calibration for target yields of different crops. Infrared spectroscopy has long been recognized as one of the most promising techniques to address the problem of time consuming, labour intensive and costly analytical processes. Mid-infrared (MIR) Fourier transform (FT) and diffused reflectance infrared Fourier transform (DRIFT) spectroscopy can be used for rapid and cost-effective precise assessment of various soil properties. Latest research trends demonstrate considerable research effort on developing near-infrared (NIR) and MIR calibrations for rapid estimation of soil parameters. Diffuse reflectance spectroscopy (DRS), comprising both the near and middle infrared regions, is emerging as a new tool to obtain information of soil and may be important step in fast, dependable and economic estimation of soil characteristics for sustainable soil management. Portable X-ray fluorescence spectroscopy, a non destructive method, is used for direct analysis of solid soil samples in the field/laboratory. It uses X-ray beams to irradiate the sample. The energy of a primary X-ray is absorbed by an electron in an atom's innermost electron shell, excitation and ejection of the absorbing electron occurs. The electron vacancies are filled by electrons from higher energy states, and X-rays are emitted to balance the energy difference between the electron states. The X-ray energy is characteristic of the element from which it was emitted and is directed to an X-ray detector in the XRF unit where it is recorded. The intensity of X-ray energy is compared to values for known standards to provide information about the unknown specimen. However, this works well for total elemental analysis of metal cations. A study under ICAR-ICRAF collaborative project, K availability indices were also ascertained through mid-infrared (MIR) spectroscopy besides traditional mineralogical approach, possibilities of. The spectra generated in MIR region were correlated with the wet chemistry value of available K under three K-availability ratings and most sensitive band was identified (Dey *et al*., 2017b).

The use of spectroscopy for soil analyses is quicker, cheaper, and less destructive than traditional wet chemistry. Additionally, it takes little sample preparation and doesn't require any chemical reagents. From the results of soil analysis, some of the outlier wet chemistry data were identified and discarded following Dixon test. The Kennard-Stone (KS) algorithm method was then used for selection of representative data subsets for calibration and validation of models from the generated soil MIR spectra. About 70% data used for development of chemometric model and 30% of soil sub-samples were used for the model validation. Before further analysis, the MIR soil spectra were transformed to first derivative using Savitzky-Golay method. Predictive models developed with PSLR techniques performed better than the other two regression techniques for all the soil properties except for available potassium and EC, where the SVM regression model performed slightly better. Good predictions for the independent validation data set were obtained for clay, silt, sand percentage, soil water retention at PWP and FC soil organic carbon content and pH in models developed through PLSR technique (Hati *et al.*, 2022). Thus MIR-spectroscopy could potentially be used for simultaneous and rapid estimation of soil organic carbon content, sand, clay, silt percentage, soil water retention, and pH. lt is also environmentally friendly because no hazardous chemicals are used. There is an urgent need of developing digital soil mapping for landscape-scale assessment of the soil health and land management using of pedo-transfer function, soil spectroscopic technologies (MIR, NIR and XRF) and use of various air born spectral sensors and handheld devices.

Use of sensors

Development of a detailed site-specific soil resource database is ultimately imperative for implementation of precision agriculture. This will not only allow the farmer to produce more efficiently but also help in the economical and efficient use of resources such as water, plant nutrients and agro-chemicals. Characterization of soil variability at field scale using the conventional approaches is labor-intensive, expensive, and time-consuming procedures. Therefore, soil sensors and sensing technology are the need of the hour to quantify the soil nutrient status rapidly on a spatial scale to allow efficient site-specific soil nutrient management and allocation of farm resources wisely and efficiently (Dey and Bhattacharyya, 2021). Chaudhari *et al.* (2022) have provided an excellent evaluation of the state-of-the-art technologies for soil and crop proximal sensing including hand-held sensors as viable, cost-effective substitutes for traditional approaches. In the current practices of soil testing, the farmers need to collect soil samples, transport the samples to the laboratory and got it analysed in laboratory, and getting results normally take up to 3 weeks or more. Proximal or ground-based sensors can collect high-resolution data rapidly and, in certain cases, even allowing real-time analysis and processing by taking measurements as frequently as once per second. Sensor-based soil analysis potentially provides several advantages over the conventional laboratory methods such as lower cost, increased efficiency, rapid and timely results, and collections of dense data sets while just traversing a field. Sensors can be single hand-held devices or mounted on vehicles for self-driven through GPS system or mobile operated by utilizing wide range of technologies and frequencies across the electromagnetic spectrum. Use of ion sensitive electrode including ion sensitive field effect transistor (ISFET) has also been used for soil analysis. Besides this, a promising method, which is potentially well suited for the in-field determination of total contents of elements in soils, including the light elements like N, is laser-induced breakdown spectroscopy (LIBS), an optical emission spectroscopy technique. LIBS based technique can be potentially used for simultaneous multi-element analysis of soil particularly for the high density soil analysis of agricultural fields in spatial scale, is measurable by LIBS. Thus, LIBS can measure multi-elements, including light elements like N and has the potential for high-density soil analysis of in spatially variable agricultural land (Erler *et al.*, 2020). Other miniaturized hand-held rugged sensors employ technologies involving micro-electro mechanical structures, thin-film filters, lasers, light-emitting diodes (LED), fibre optic assemblies, and high-performance detector arrays. Besides this, rapid and non-destructive quantification of spatially-variable soil nutrients can be made possible with on-the-go or hand-held sensors using optical, or electromagnetic sensors. Castrignanò *et al.* (2012) have demonstrated that the issue of commonly used EMI sensors failing to distinguish between contrasting soils encountered across some fields and landscapes can be addressed by using multiple-sensors, each with sensitivity to specific soil attributes that complement the sensitivities of other sensors. Nano-sensors and smart delivery systems can monitor and optimize irrigation and nutrient application. Nanoscale sensors embedded in soils or plants can provide real-time data on moisture levels, nutrient availability, and plant health. This allows for precise and efficient resource management. Nanotechnology can support precision farming and forestry practices by providing high-resolution imaging, monitoring, and sensing capabilities. Efforts should also be made towards development of hand held cost effective NDVI sensors to reproduce the results of commercial GreenSeeker.

One prominent real-life example is the use of satellite imagery and remote sensing in precision agriculture. Companies like The Climate Corporation, a subsidiary of Bayer, have developed platforms such as Climate FieldView™ that utilize satellite imagery to monitor crop health and make fertilizer recommendations. The platform collects high-resolution satellite imagery throughout the growing season, which is then processed using advanced algorithms to identify crop stress, nutrient deficiencies, or excessive vegetation growth. Based on these insights, farmers receive precise fertilizer recommendations tailored to specific areas of their fields. Another example is the integration of soil sensors and data analytics. Companies like SoilOptix use electromagnetic soil scanning technology to measure soil composition and nutrient levels. These sensors are mounted on vehicles that drive across fields, capturing detailed soil data in real-time. The collected data is then analyzed using sophisticated algorithms, which generate comprehensive maps showing variations in soil fertility within the field. Farmers can use these maps to create prescription maps for variable-rate fertilizer application, ensuring that nutrients are precisely targeted where they are needed most. These examples highlight how smart technologies are transforming fertilizer recommendations by providing accurate and site-specific insights. By leveraging satellite imagery, remote sensing, and soil sensors, farmers can make data-driven decisions to optimize fertilizer usage, enhance crop health, and improve overall soil management. It's amazing to see how these technologies are changing agriculture and enabling farmers to make better, more informed decisions for better crop and soil health management!

Agricultural Internet of Things

The Agricultural Internet of Things (AIoT) is the digital disruption to transform agri-operations from field reparation, sowing, input application and final harvesting. This is possible with the advent of artificial intelligence, machine learning, cloud and mobile connectivity; field characterisation through internet connected devices like drones, remote sensing and hand-held sensors for geo-tagging of each parcel of land and development and delivery of advisory regarding farm management plans through cloud based network will help in increasing farm profitability and achieving soil sustainability (Dey and Bhattacharyya, 2021). Because of their portability and flexibility to specifically designed electrical systems, Internet of Things (IoT) based solutions might be developed fairly easily (Archbold Taylor *et al.*, 2019). Enumeration of spatial variability with help in introducing variable-rate technology (VRT) for application of plant nutrient, agro-chemicals, amendments, irrigation water and other farm inputs by automated rate settings on applicators/equipment with saving in energy due to m minimising passes in the field.

Smart technology vis-à-vis increasing efficiency of the input

Increasing use efficiency through adoption of technological options and management strategies including ICTs and mobile apps for location specific soil and nutrient management is important for increasing farm profitability and reduce agrarian distress. Digital agriculture, incorporating technologies such as Artificial Intelligence (AI), Machine Learning, Cloud Computing, Satellite Imagery, block chain and advanced analytics have great potential in empowering small-holder farmers to increase their income through higher crop yield and greater price control (Dey, 2019). Land governance, extension and advisory services, finance and markets, local governance and cooperation models, together with monitoring and evaluation at all stages are important for development of policy matrix towards sustainable soil management and climate resilient agriculture (Dey, 2020). Stacking big data approaches such as understanding the nutrient stock, understanding the use efficiency vis-à-vis crop demand, accounting for residues as well as cropping system, and synchronizing with plant need are important for increasing efficiency without incurring yield penalty. Application of machine learning in remote sensing has been applied successfully under field condition (Arab *et al.*, 2021). Giving proper credit to other nutrient sources, such as legumes, manure, and irrigation water is also vital for trustworthy recommendation. There is an urgent need to come up with the consensus on principles of building blocks for more dynamics of recommendation with input from AICRP (STCR). Based on the data analytics, we can verify at the field level and develop the framework including different varieties etc. for use efficiency and yield. Crop demand is not just from nutrient but other factors need to be integrated to determine the efficiency and yield; slope, depth and texture should be taken into consideration.

Conclusion and way forward

During *Amrit Kaal*, we need a paradigm shift towards a coherent system of soil research rather than silos. There is an urgent need for adoption of efficient nutrient management harnessing geo-spatial technologies like global positioning systems (GPS), geographical information systems (GIS), remote sensing, geostatistics and variable rate applicators to optimize various agricultural inputs. Enumeration of soil spatial variability and preparation of GPS/GIS-based soil fertility maps will help adoption of variable rate technology (VRT) for application of plant nutrients and amendments by automated rate settings on applicators/ equipment with input saving and profit maximization. GPS/GIS-based soil fertility maps together with STCR prescription equations can also be used for development of customized fertilizer formulations. In addition, leveraging private investment and initiative is utmost important for development of customized fertilizers and adoption of VRT. Future research on smart nutrient recommendation should also address and customize the supply channel modifications to reach the vulnerable groups of malnourished women, children, elderly and sickly people and allowing their accessibility to nutritious food through adequate balancing of yield and quality. Halting and reversing land degradation as well as sequestering soil organic carbon through smart management is a high priority for transitioning to achieve a land-degradation neutral world in the context of sustainable development. The concept of Land Degradation Neutrality (LDN), as enshrined in Target 15.3 of SDG, should be the guiding principal for adoption and implementation of smart nutrient management technologies.

Such technologies also contribute to sustainable agriculture by promoting precision farming practices. By providing optimal plant nutrient recommendations, they help conserve resources, reduce chemical runoff, and mitigate the risk of nutrient pollution. Additionally, smart technologies support soil health management by ensuring that the soil's nutrient balance is maintained, leading to improved fertility and long-term sustainability. In summary, smart technologies have enough potential to transform plant nutrient recommendations by offering precise, data-driven insights that enhance crop and soil health management; will empower farmers to make informed decisions, optimize resource utilization, and promote sustainable agricultural practices.

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Recent Advances in Dissemination of Agro Advisory Services in India

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The primary factor influencing agricultural productivity is the climate. Extreme weather and climatic variability have emerged to be major threats to India's crop production in recent years. Between 1901 and 2018, there was an average 0.7 °C increase in temperature in India (Krishnan *et al*., 2020). According to the RCP8.5 scenario, by the end of the twenty-first century, there will be a fifty percent rise in warm nights and a fifty percent increase in warm days relative to the reference period of 1976-2005. The severity and frequency of extreme weather occurrences, such as heavy precipitation, cloud bursts, hailstorm events, droughts, etc., have risen due to climate change. Food production will become more unstable due to the anticipated rise in cyclones, heat and cold waves, droughts, floods, and extreme precipitation events.

When it comes to planning inputs and making the best use of them during the crop season, farmers can greatly benefit from the availability of accurate meteorological information. Stable agricultural production should be achieved despite the growing population's shifting dietary patterns and rising food demand. Thus, preparing for climate change scenarios in India requires a thorough understanding of abiotic stresses, including type, impact, mechanism, and tolerance elements for adaptation strategies, across various future climate scenarios and locations (Bal and Minhas, 2017).

Science and technology have advanced at an enormous rate in the twenty-first century. The target population, farmers, will receive accurate and timely information thanks to our growing understanding of weather forecasting and the use of cutting-edge IT systems. However, there is a significant disconnect between the farmer and the information source. Not all of the farmers in our nation are tech-savvy, and it is still difficult to include small and marginal farmers in the agromet advice network. In addition, new hazards brought up by climate change and variability highlight the necessity of bolstering nowcasting. As a result, the problems associated with weather and climate stress that need to be addressed by agromet advisory services are growing and becoming more complicated.

Improvement of weather forecasting in India

The use of science and technology to forecast the atmospheric conditions for a certain place and time is known as weather forecasting. Accurate information on the actual weather conditions of the locality about all-weather aspects at the time of forecasting is required, in addition to knowledge about the average and seasonal weather conditions of the area. Since its founding in 1875, the India Meteorological Department (IMD) has steadily increased the extent of its infrastructure for meteorological communications, observations, forecasting, and weather services. It used weather telegrams extensively for observational data collection and warning dissemination during the telegraph era. Subsequently, IMD became the first Indian organization to support its international data interchange with a message-switching computer. IMD received one of the first electronic computers ever introduced in the nation for use in meteorological science applications. With its own geostationary satellite, INSAT, India was the first developing nation in the world to continuously monitor the weather in this region of the world, especially for cyclone warnings.

With a spatial resolution of 250 km in the medium range (3 days), the National Centre for Medium-Range Weather Forecast (NCMRWF) has been providing quantitative weather forecasts for a total of 5 agrometeorological field units (AMFUs) since 1991. The spatial resolution was increased to 150 km in 1993 and then to 75 km in 1999. In 2006, the forecast's temporal resolution at the agroclimatic zone level was increased from three to five days. In 2007, the AMFU network—which covered all agroclimatic zones with 130 units in 2007 as opposed to 5 units in 1991—merged these two forecast systems, the NCMRWF and IMD, into a single system. Different types of weather forecasts provided by IMD which has applications in agriculture are depicted in Fig. 1. On an experimental basis, IMD started issuing medium-range weather forecasts at block-level since 2014. One of the targets of IMD will be to issue village-level weather forecasts shortly, which will enable agricultural scientists to prepare location-specific agromet advisories.

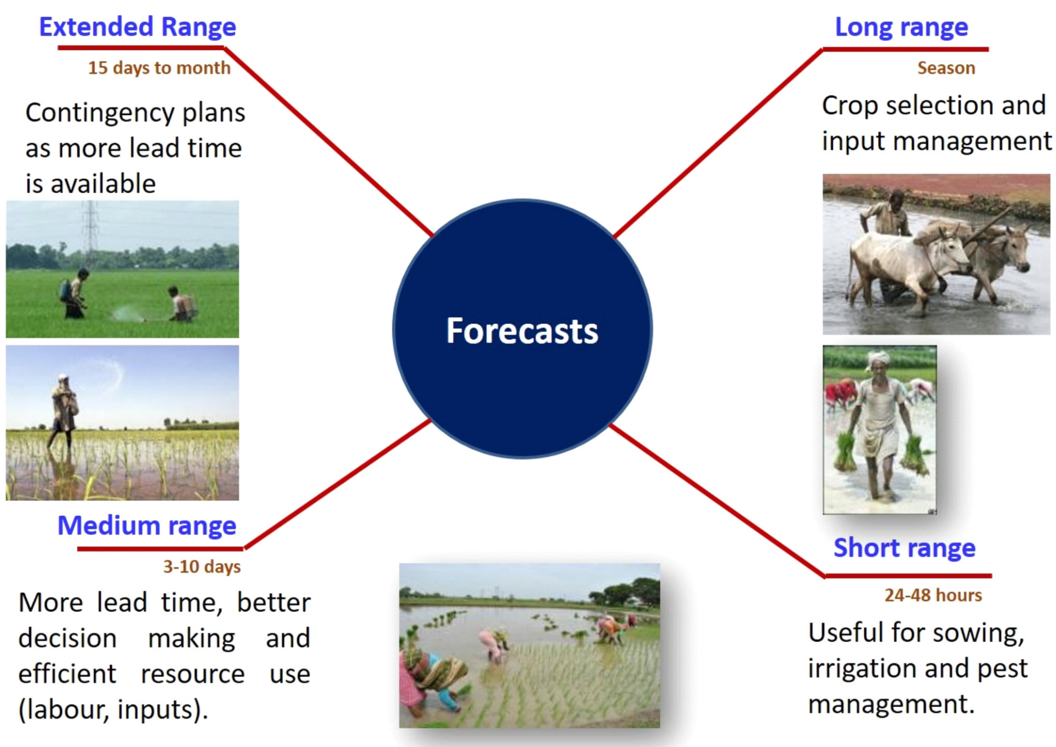

Figure 1. Types of weather forecasts issued by IMD and its applications in agriculture

History of Agromet Advisory Services in India: development and dissemination

All agrometeorological and agro-climatological information that may be immediately utilized to improve and/or protect the livelihoods of farmers is referred to as AAS (Stigter 2011). AAS was introduced by the India Meteorological Department over All India Radio in 1945 as the farmers' weather bulletin (FWB). In cooperation with state agriculture departments, IMD launched AAS in 1976 through its state meteorological centers. The National Centre for Medium-Range Weather

Forecast (NCMRWF) started generating quantitative weather forecasts in the medium range (3 days) with a spatial resolution of 250 km for a total of 5 agrometeorological field units (AMFUs) in 1991. In 1993 and 1999, the spatial resolution improved to 150 km and 75 km, respectively.

As the AMFU network expanded from 5 units in 1991 to 130 units in 2007 to cover all ACZs, these two systems (the NCMRWF prediction system and the IMD forecast system) merged into a single system. IMD started providing district-level multimodel ensemble weather forecasts on June 1st, 2008, with a spatial resolution of 50 km and a temporal resolution of 5 days. AAS is an interdisciplinary and multi-institutional project at the moment. In addition to IMD, it also involves state agricultural departments, nongovernmental organizations, state agricultural universities, the media, and the Indian Council of Agricultural Research (ICAR). The flow diagram of AAS and interinstitutional linkages are depicted in Fig. 2.

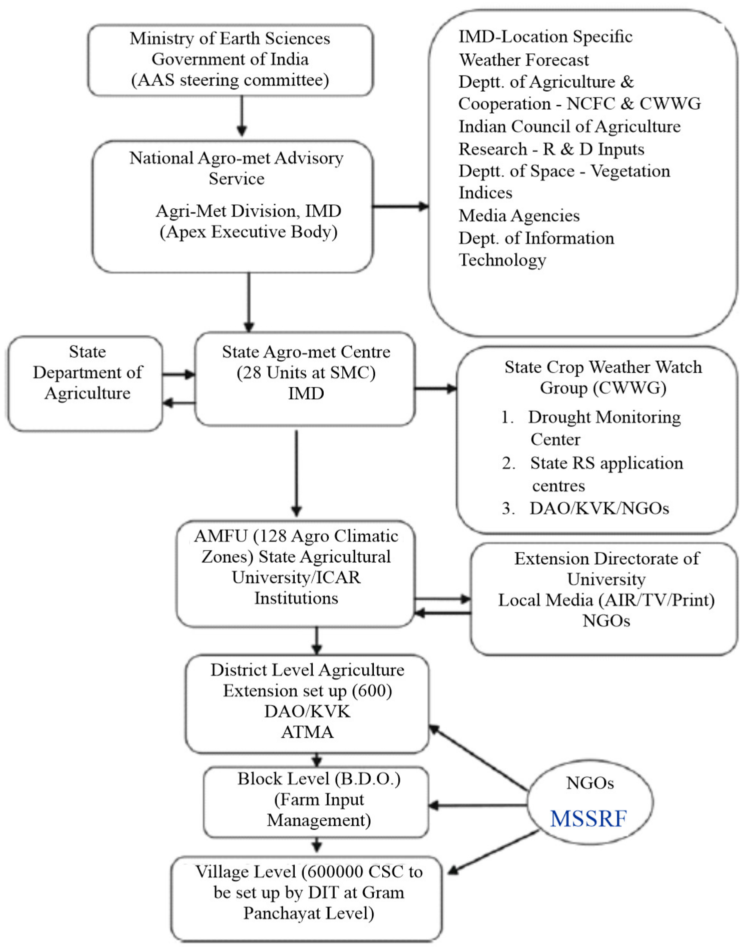

Figure 2. Flow diagram of integrated AAS and inter-institutional linkages (Rathore *et al*., 2011)

Micro-level Agromet Advisory Services (MAAS) by ICAR

Though the spatial resolution of medium-range weather forecasts has been improved to the district level, the practical applicability of these advisories is grossly inadequate to implement at the farmers' level. This is because a district's crop types, varieties, and climatic conditions—particularly rainfall—vary greatly over space. To solve these problems, the 25 collaborating centers that makeup

AICRPAM of ICAR launched a pilot project in 2011 to develop and disseminate block-level AAS on a pilot basis. It utilizes the IMD's block-level weather forecast. In this case, subject matter experts from Krishi Vigyan Kendras—KVKs—assist the AICRPAM center's agrometeorologist in developing the AAS bulletins (Vijaya Kumar *et al*. 2017). To achieve this, the Field Information Facilitator (FIF) gathers field-level data (such as crop types, development stages, and the prevalence of pests and diseases) and provides the farmers with the developed AAS. FIF serves as a point of contact for farmers, KVK, and the AICRPAM center. Fig. 3 shows the methodology that was developed for the generation and dissemination of MAAS.

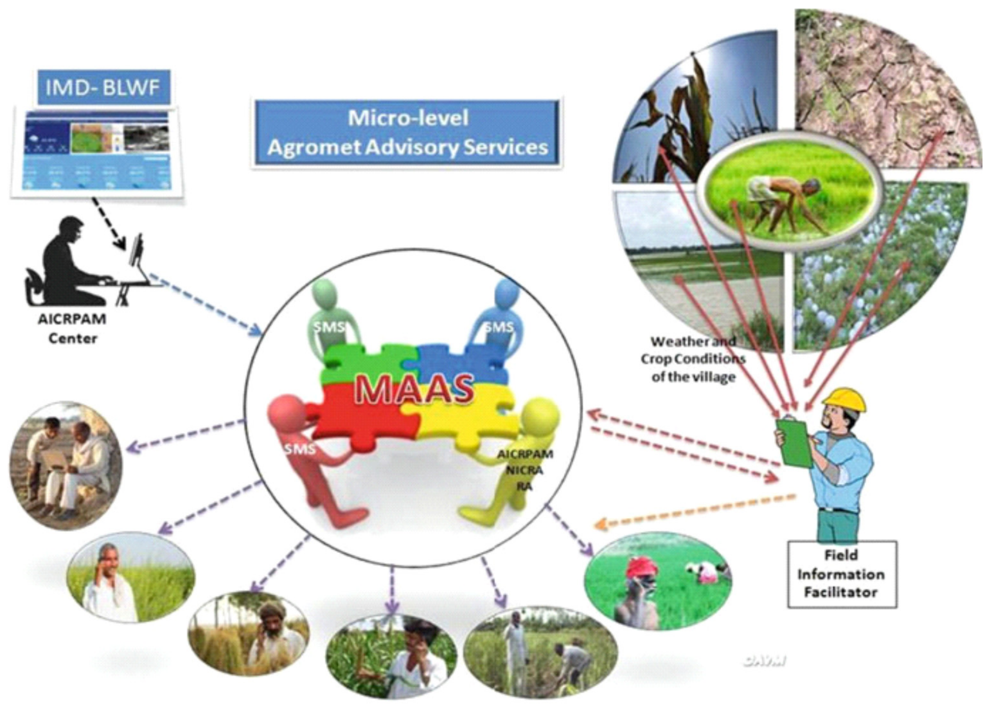

Figure 3. Development and dissemination of MAAS (Vijaya Kumar *et al*. 2017)

Dynamic Crop Weather Calendar (DCWC)

AICRPAM has recently developed dynamic crop weather calendars (DCWC) for automating agromet advisories using prevailing and forecasted weather (Vijaya Kumar *et al.*, 2021). To make farmers self-reliant, sensitizations of the farmers are necessary and provision of timely and accurate AAS with suitable crop management advisory is to be ensured (Bal and Sarath Chandran, 2020).

Economic Impact Assessment of AAS

By giving farmers accurate information about anticipated in-season weather, AAS hopes to boost their profits by ensuring optimal resource utilization and minimizing losses and waste. Impact assessment is the most crucial instrument for determining a project's viability.

The economic impact of the medium-range weather forecast issued by NCMRWF was assessed in a pilot study in 15 out of 127 agromet field units (AMFUs) under which AAS was issued (Maini and Rathore 2011). They had selected six cropping seasons (three kharif [southwest monsoon] and three rabi [winter] seasons) that were chosen for the study during 2003-07. The crops selected for the study included food grains, cash crops, oilseeds, fruits and vegetables. The sample size of the study consisted of 80 farmers, out of which 40 were AAS following and 40 were AAS non-following. The main objective of the study was to quantify the change in yield and net return due to AAS. The major finding from the study was farmers who followed AAS fetched 10–15% higher yield and 2–5% reduction in the cost of cultivation compared to the AAS non-followers.

A study conducted by the National Centre for Agricultural Economics and Policy Research (NCAP) concluded that farmers received 10–25% economic benefit due to the adoption of AAS. Another assessment by the National Council of Applied Economic Research (NCAER) revealed that the economic benefit of AAS as Rs. 50,000 crores per year in 2009, when extrapolated, increases to Rs. 211,000 crores if all the farmers of the country are using AAS in their decision-making during crop season (Chattopadhyay and Chandras, 2018). NCAER again conducted another study and reported that only 24% of the total farmers of India had access to AAS from SMS services, which accounted for an economic profit of Rs. 42,000 crores (NCAER 2015). They also reported that if AAS is utilized by all farming households, it has the potential to create economic benefits up to ' 3.3 lakh crores on the 22 principal crops.

Future challenges

In many parts of India, the rise in extreme weather occurrences including hailstorms, cloud bursts, and heavy rains is seriously damaging crops. Even though IMD is providing "nowcast bulletins" and "special weather bulletins," there is still room for improvement in the forecast's accuracy. The advent of ICTs for the dissemination of AAS has enabled the service to provide agencies to cover masses of farmers. But, still, many rural farmers don't have mobile phones and access to the internet. It has been noted that different AAS-providing agencies are giving the same farmer different AAS for the same period, which is confusing them. Although IMD is issuing block-level weather forecasts, AAS based on the block-level weather forecast is not upscaled to the national level. The ultimate aim of AAS will be customized advisories at the farmer level. That will require weather forecasts with farm-level spatial resolution, farmer-level crop and soil information, and huge computing skills for the automation of AAS.

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Role of Crop Simulation Models in Digital Agriculture

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Technological changes during the past century, such as the Green Revolution, have transformed the phase of agriculture. Despite the doubling population and tripling food demand since the 1960s, global agriculture has been able to meet the demands with only a 30% expansion in the cultivated area (Swaminathan, 2006). The demand for food and agricultural products is projected to further increase by more than 70% by 2050. The current yield trends are insufficient to double crop production by 2050, the actual trends for the rate of increase of crop yields for maize, rice, wheat and soybean should be increased to 2.4% to feed the 9 billion people by 2050 (Ray *et al.*, 2013). Traditional agricultural decision-making, based on empirical knowledge and experience, is encountering the limitations of managing this complexity. For an economically and environmentally sustainable production system, there is a need to develop techniques that can increase crop production through increased efficiency of inputs use and reduced environmental losses. The agricultural sector faces multiple challenges, including the need to meet the rising global demand for food, adapt to changing climatic conditions and minimize environmental impact.

Digital agriculture has emerged as a transformative force in modern farming practices, leveraging technology to enhance efficiency, sustainability, and productivity. Digital agriculture, at the intersection of agriculture and cutting-edge technologies, has emerged as a catalyst for reshaping traditional farming practices. Digital Agriculture is "ICT and data ecosystems to support the development and delivery of timely, targeted information and services to make farming profitable and sustainable while delivering safe nutritious and affordable food for ALL." (ICRISAT). Every link in the agri-food production chain is going to evolve as a result of digitalization because it enables instantaneous processing of vast amounts of information and connectivity, which improves productivity, yields higher financial returns, protects the environment, and creates better working conditions for field workers (Bolfe *et al.*, 2020). One crucial component of this transformation is the integration of crop simulation models, which play a pivotal role in optimizing crop management for sustainable and efficient food production. These models provide computational power to simulate and predict the complex interactions between various factors affecting crop growth, enabling farmers to make informed decisions and adapt to ever-changing environmental conditions (Rotter *et al.*, 2015). Crop simulation models are computer-based tools that simulate the growth and development of crops in response to different environmental factors, management practices, and genetic characteristics. These models incorporate a multidisciplinary approach, integrating agronomy, meteorology, soil science, and plant physiology to create a comprehensive representation of the crop growth process (Hodson and White, 2010). The primary goal is to provide farmers with a virtual environment where they can test different scenarios, evaluate potential outcomes, and optimize their decision-making processes (Whistler *et al.*, 1986). Hence it is important to understand the role of crop simulation models in digitization of agriculture.

Crop Simulation Models

Crop simulation models are pivotal tools in the realm of digital agriculture, offering dynamic insights into the complex interactions between crops and their environment. Several models have been developed, each with unique features and advantages tailored to diverse agricultural contexts. One prominent model is the Decision Support System for Agrotechnology Transfer (DSSAT). DSSAT stands out for its comprehensiveness, integrating sub-models covering crops, soil, and weather (Jones *et al*., 2003). This holistic approach provides farmers with a comprehensive view of their agricultural system. Its versatility allows it to support a wide range of crops, making it applicable in diverse agroecological zones. Moreover, DSSAT's capability for long-term simulations enables the analysis of crop responses over multiple growing seasons (Thorp *et al*., 2008). Another influential model is the Agricultural Production Systems sIMulator (APSIM), known for its modular structure. APSIM's design allows for flexibility and customization, adapting easily to different crops and farming systems. It excels in simulating complex cropping systems, including rotations and cover crops, offering a detailed understanding of soil health (Keating *et al*., 2003). The model's modular approach also facilitates the integration of various biophysical processes, enhancing accuracy. CERES, or Crop Estimation through Resource and Environment Synthesis, is a widely adopted model recognized for its process-based simulation. It dives into the physiological processes of crops in response to environmental variables, providing a detailed understanding of growth dynamics (McCord and Sotin, 2005). CERES offers calibration features, allowing users to fine-tune the model for specific crop varieties and local conditions, contributing to its widespread global adoption. Aquacrop specializes in simulating crop growth under water-limited conditions, making it invaluable in arid and semi-arid regions. Known for its user-friendly design, Aquacrop requires less input data compared to some other models, making it accessible to a broader range of users. It provides detailed insights into crop responses to drought stress, aiding in drought risk management (Vanuytrecht *et al*., 2014). Common advantages across these models include their role in facilitating precision agriculture, optimizing resource use, and offering decision support for farmers. The selection of a specific model depends on factors such as the targeted crops, geographical location, and specific research or management objectives (Muller and Martre, 2019). As technology advances, these models continue evolving, offering more sophisticated and accurate representations of the intricate interactions within agroecosystems. All these models help in increasing resource use efficiency and making agriculture sustainable. Thus, they have a wider role to play in the digitization of agriculture.

Benefits of Crop Simulation Models in Digital Agriculture

The role of crop simulation models in digital agriculture is instrumental, in revolutionizing the way farmers manage their crops, make decisions, and adapt to the complexities of modern agricultural systems. These sophisticated computer-based models have become indispensable tools, providing a virtual platform to simulate, analyze, and optimize crop growth under various environmental, genetic, and management conditions. Their pivotal role in digitizing agriculture is explained under subheadings,

Precision Agriculture

Precision agriculture, facilitated by crop simulation models, constitutes a transformative approach to crop management. These models enable farmers to finely calibrate their practices by considering the inherent variability across their fields. Spatial and temporal precision allows for a nuanced understanding of soil characteristics, microclimates, and weather patterns (Basso *et al*., 2001). The application of crop simulation models in precision agriculture extends to the implementation of Variable Rate Technology (VRT). These models guide the precise adjustment of inputs, such as fertilizers or irrigation, based on the anticipated impact on crop growth. The result is optimized resource use and enhanced overall farming efficiency (McKinion *et al.*, 2001).

Decision Support Systems

Crop simulation models serve as dynamic decision support systems, providing farmers with a virtual laboratory for testing different scenarios. Through scenario analysis, farmers can explore the consequences of various decisions, such as changing crop varieties, adjusting planting dates, or modifying irrigation practices (Thorp *et al.*, 2008). Resource allocation is a critical aspect of decision-making in agriculture. Crop simulation models assist farmers in optimizing the allocation of land, labor, and capital by providing insights into the potential outcomes of different allocation strategies. This enables farmers to make informed decisions that align with their objectives and maximize overall efficiency.

Risk Mitigation

In the realm of risk mitigation, crop simulation models offer a proactive approach to addressing uncertainties in agriculture. These models can simulate the impact of extreme weather events, such as droughts or floods, helping farmers anticipate challenges and implement strategies to mitigate potential losses (Challinor *et al.*, 2018). Pest and disease outbreaks pose significant risks to crop production. Crop simulation models contribute to integrated pest management strategies by simulating the potential impact of these biotic stresses. Farmers can explore the effectiveness of different pest control measures, minimizing the reliance on chemical interventions and promoting sustainable practices.

Resource Efficiency

Efficient use of resources is a cornerstone of sustainable agriculture, and crop simulation models play a pivotal role in achieving this goal. These models assist in optimizing water use efficiency by simulating the water requirements of different crops under varying conditions. Nutrient management is another critical aspect of resource efficiency. Crop simulation models simulate nutrient cycling and uptake, aiding farmers in optimizing fertilizer application. By understanding how different crops respond to varying nutrient levels, farmers can adjust their practices to ensure that crops receive the right amount of nutrients, minimizing excess applications that can lead to environmental pollution (Jongschaap, 2006).

Climate Change Adaptation

Crop simulation models are invaluable tools for farmers seeking to adapt to the challenges posed by climate change. These models simulate how different crops respond to changing climatic conditions, allowing farmers to proactively adjust their practices. Adaptation strategies may also involve changes in land use practices. Crop simulation models can simulate the impact of such changes, helping farmers explore alternative cropping systems or agroforestry practices that enhance resilience to climate change (Asseng *et al.*, 2015).

Research and Development

In the realm of research and development, crop simulation models serve as dynamic tools that drive innovation in agriculture. Researchers use these models to calibrate and validate their simulations against real-world data, ensuring the accuracy and reliability of their predictions (Miglietta and Bindi, 1993). Continuous improvements in crop simulation models contribute to the overall knowledge base in agriculture. Researchers can explore the interactions between different factors influencing crop growth, test hypotheses, and refine agricultural practices. This iterative process of model development and validation fosters innovation and sustainability in agriculture.

Educational Tool

Crop simulation models also serve as valuable educational tools, enhancing the understanding of agricultural systems among farmers, agronomists, and students. These models provide a visual representation of complex agricultural concepts, making it easier for individuals to grasp the relationships between various factors affecting crop growth. Hands-on learning is a significant aspect of agricultural education, and crop simulation models facilitate this by providing a virtual platform for experimentation. Students and farmers alike can interact with these models, testing different scenarios and gaining practical insights into the intricacies of agricultural systems.

Conclusion

In conclusion, the role of crop simulation models in digital agriculture extends far beyond numerical predictions. These models empower farmers, researchers, and educators to explore, understand, and optimize the intricate dynamics of crop growth. From precision agriculture and decision support to risk mitigation and adaptation to climate change, crop simulation models contribute to more sustainable, resilient, and efficient agricultural systems. As these models continue to evolve, their role in shaping the future of agriculture becomes increasingly critical.

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Regenerative Agriculture for Sustainable Production and Environment: Concept, Prospects and Research Needs

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Introduction

Climate change is an alarming global issue caused by the excessive release of greenhouse gases, predominantly from human activities such as burning fossil fuels and deforestation (IPCC, 2018). The consequences of climate change are widespread and include rising global temperatures, increased frequency and severity of extreme weather events, melting glaciers, sea-level rise, and disruptions to ecosystems and biodiversity (NASA, 2023). To combat climate change, it is essential to mitigate greenhouse gas emissions, transition to renewable energy sources, promote sustainable practices, and implement policies that prioritize environmental conservation (UNFCCC, 2023). Countries are off track to fulfill their nationally determined contributions (NDCs) for climate change. Based on present policies, global greenhouse gas (GHG) emissions in 2030 are projected to reach 58 Gt CO_2e. However, to align with the goal of limiting global warming to 1.5°C, annual GHG emissions need to be reduced by 45% compared to the estimated emissions under current policies by 2030 (UNEP, 2022). The food system is currently responsible for about a third of total GHG emissions (18 Gt CO_2e/year). Emission from agriculture comes from production of inputs such as fertilizers (7.1 GtCO_2e, 39%) followed by changes in land use (5.7 Gt CO_2e, 32%) and supply chain activities (5.2Gt CO_2e, 29%). To reduce the emission from agriculture, land use must transition rapidly from being a net source of emissions to a net sink. There is high requirement of necessary changes in agricultural systems to offset GHG emission which includes a) demand-side changes, including dietary changes b) protection of natural ecosystems, including reductions in deforestation and land degradation c) improvements in food production at the farm level, including changes in the composition of animal feeds, better rice management, better nutrient management d) decarbonizing the food supply chain, including in retail, transport, fuel use, industrial processes (UNEP, 2022). FAO (2017) estimates that agricultural production must increase by about 50% by 2050 to meet the needs of the growing human population and against a backdrop of shrinking farmland. Policymakers and stakeholders are increasingly interested in climate resilient agricultural practices. During COP28, the Emirates Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action was signed by 134 nations at the World Climate Action Summit (WCAS). These nations account for 5.7 billion people, nearly 500 million farmers, and a quarter of global emissions. The agreement entails a $2.5 billion investment in advancing the food and climate agenda, emphasizing the pursuit of the 1.5-degree goal through the promotion of emission-reducing technologies. The COP28 Regenerative Landscapes Action Agenda, led by the COP28 Presidency, World Business Council for Sustainable Development (WBCSD) and the Boston Consulting Group (BCG) and supported by the UN High Level Climate Champions (HLCC), seeks to consolidate and boost initiatives to shift major agricultural landscapes to regenerative practices by 2030 (WBCSD, 2023). Regenerative landscapes prioritize the restoration and enhancement of ecosystem functions and aim for 160 million hectares under RA by 2030, a $2.2 billion investment will empower 3.6 million farmers globally. This multifaceted approach involves financial incentives, technical support, government policies, R&D, and education. This collaborative, science-driven initiative by OP2B engages farmers, scientific communities, and civil society to implement a RA framework. Its goal is to aggregate, accelerate, and amplify existing and new commitments and focus on restoring ecosystems, managing water sustainably, and enhancing soil health, impacting both farm-level and broader ecosystem outcomes.

Concept and Genesis of Regenerative Agriculture

The term "regenerative agriculture (RA)" was first coined by Gabel (1979). Rodale (1986) further developed the concept of regenerative organic farming (Khangura *et al*., 2023).

Regenerative Agriculture is an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production (Schreefel *et al*., 2020). Regenerative organic agriculture prioritizes soil health (fewer annuals and more perennials), reducing and ultimately eliminating the use of harmful chemicals, integrating animals onto agricultural land, and cultivation strong relationships with communities (NRDC, 2021). According to RAI (2017), RA involves the practices that: (i) contribute to generating/building soils and soil fertility and health; (ii) increase water percolation, water retention, and clean and safe water runoff; (iii) increase biodiversity and ecosystem health and resiliency; and (iv) invert the carbon emissions of the current agriculture to one of remarkably significant carbon sequestration thereby cleansing the atmosphere of legacy levels of CO_2. Wilson *et al*. (2022) studied the perspectives of farmers, private companies, researchers, and NGOs about RA across USA and identified three groups of conclusions: climate adaptation and mitigation, socio-economic benefits, and integrated systems (Figure 1). Their perspectives about

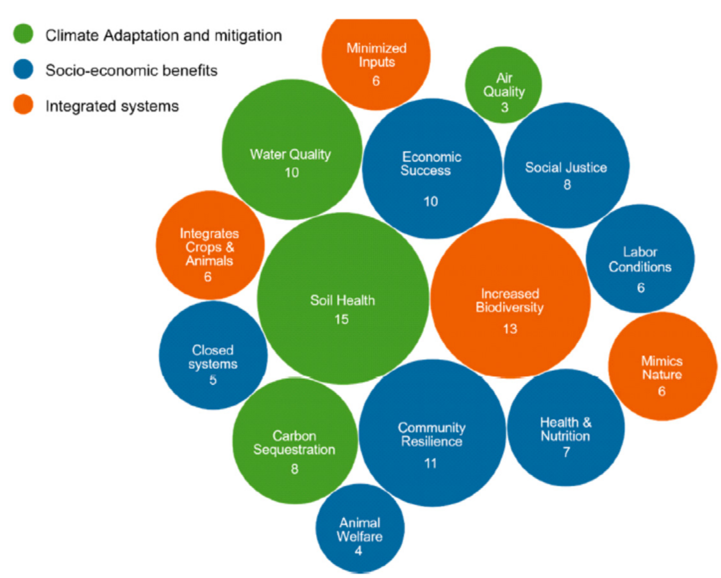

Figure 1. Perspective of farmers, private companies, researchers, and NGOs about Regenerative Agriculture across USA (Wilson *et al*., 2022)

RA were further sub-categorized as soil health, increased biodiversity, community resilience, water quality, economic success, carbon sequestration. Hence, there is wide array of definition and key focus points according to different stakeholders about RA worldwide and the concept was identified as a holistic and convergent approach covering provisioning, supporting, regulating and cultural services.

Many sustainable agriculture options are in practice worldwide *viz.*, organic farming (OF), conservation agriculture (CA), sustainable intensification and agroecology. The loopholes in the existing sustainable agriculture practices (Bless *et al.*, 2023), namely, the organic farming attempts to escape market niche status, CA lacks livestock integration and relies on external inputs, association of sustainable intensification with productivism and industrial agriculture and resistance of agroecology towards corporations and external actors have led to the development of RA concept with a holistic approach (Figure 2).

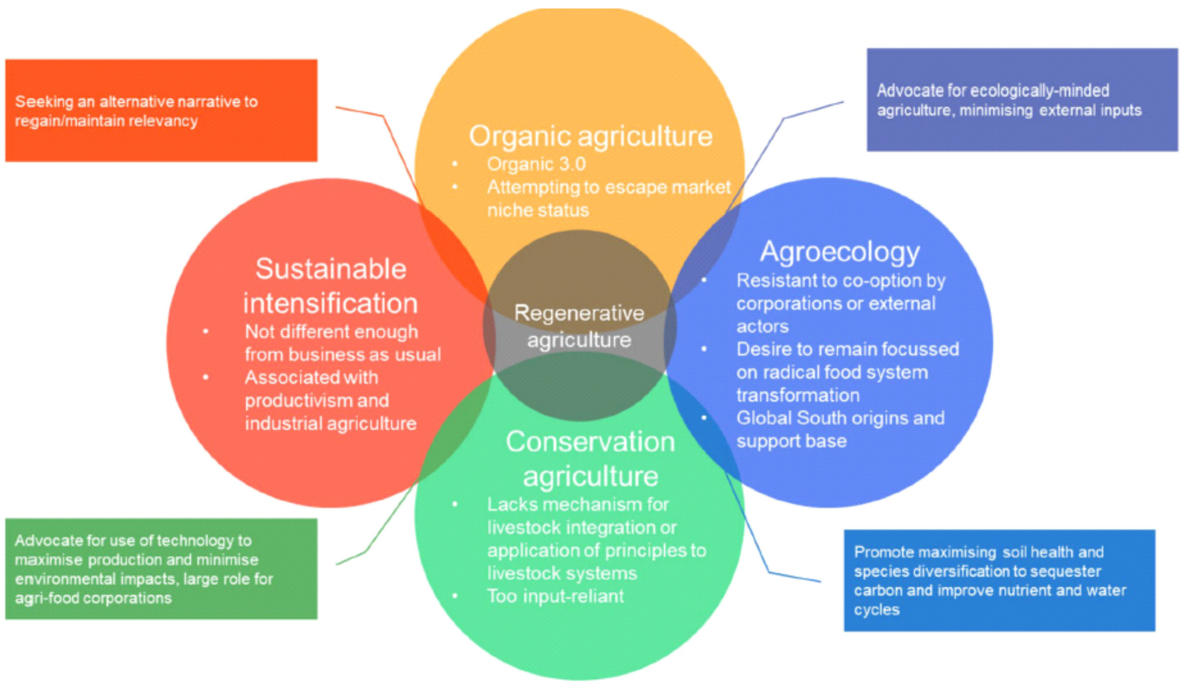

Figure 2. Loopholes in the existing sustainable agriculture practices that led to regenerative agriculture emergence (Bless *et al.*, 2023)

Principles of Regenerative Agriculture

Regenerative agriculture is guided by a set of principles (Figure 3) that prioritizes the soil health improvement, biodiversity, economic resilience in farming communities and ecosystem function. These principles are:

1. Minimize soil disturbance.
2. Maximizing crop diversity.
3. Keep the soil covered.
4. Maintain living Root Year-around.
5. Integrating livestock into cropping systems.

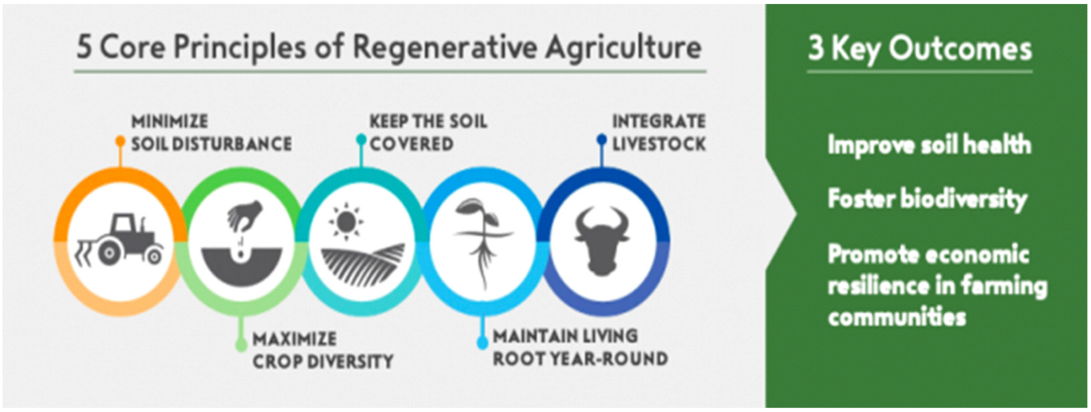

Figure 3. Principles of Regenerative Agriculture (Sweet living Farms, 2023)

Regenerative Agriculture Practices and Associated Benefits

Cover cropping

Cover cropping in agriculture involves planting non-cash crops like legumes or grasses between main crops, safeguarding soil, reducing erosion, suppressing weeds, and promoting water retention for a more sustainable farming approach. Nouri *et al*. (2019) demonstrated that long-term incorporation of cover crops, in conjunction with NT improved the physical properties of soil, such as soil aggregation and moisture retention during dry spells. A meta-analysis of 131 worldwide studies (Jian *et al*., 2020) revealed that integrating cover crops into rotations significantly increased soil organic carbon (SOC), especially in fine-textured soils and more prominently in shallow soil (30 cm) compared to subsurface (>30 cm).

No-till/Reduced tillage

No tillage or reduced tillage minimizes soil disturbance, preserving structure, organic matter, and microorganisms, reducing erosion and nutrient loss. Haddaway *et al*. (2017) found a global meta-analysis indicating a 4.6 Mg/ha increase in carbon stock under no tillage versus intensive tillage (0–30 cm) over 10 years. Martinez *et al*. (2013) observed improved soil fertility with higher N, P, and K levels in irrigated Mediterranean no-till systems. Global analysis (Sun *et al*., 2020) shows conservation agriculture benefits arid regions, achieving increased carbon sequestration and crop yield, while in humid areas, only soil organic carbon gains are likely.

Crop diversification and agroforestry

Crop diversification mitigates risks of failure, pests, and diseases by breaking monoculture cycles, fostering natural pest control, and enhancing disease resistance. It improves soil health, biodiversity, and economic outcomes by diversifying marketable products. Intercropped legumes contribute to stable soil organic matter formation. Das *et al*. (2020) evaluated the soil health under various crop establishment methods in rice- mustard cropping system and found that adopting residue retention in ZT direct seeded rice followed by ZT mustard followed by ZT mungbean system was found superior to other ZT and conventional systems for soil quality index in 0-5 and 5-15 m soil depths. Agroforestry, combining trees with crops or livestock, offers benefits like enhanced soil fertility, increased biodiversity, carbon sequestration, and improved water management, providing sustainable solutions for resilient and eco-friendly agriculture. The LOME concept (Dent and Boris,

2021) is a food-plus energy system based on Legumes (providing nitrogen and energy), Oilseeds (energy) and Methanation of biomass (both plant and animal waste).

Mulches and Compost

Retaining crop residues as mulch and utilizing compost enhance soil biodiversity, structure, and nutrient cycling, contributing to improved carbon sequestration. Despite compost's rapid impact on soil organic carbon and aggregate stability, challenges in supply and transportation costs may arise, particularly in smallholder agriculture. Integrated crop-livestock systems, incorporating manure and crop residues, prove effective in carbon sequestration, soil function improvement, and erosion mitigation. Cover cropping, mulches, and compost application promote below-ground biodiversity, crucial for stable soil carbon formation. The complex soil community, influenced by farming practices, builds carbon stores through interactions with physical structures, living roots, and decomposing organic matter. To optimize carbon storage, farmers focus on diverse carbon inputs, fostering microbial biomass and forming necromass-mineral amalgams through a variety of plant roots. Managing microbial carbon use efficiency, maintaining a proper carbon-to-nitrogen ratio, and incorporating high-quality inputs such as legume cover crops and manure are essential for effective soil carbon sequestration.

Nitrogen improvement through composting, mulches, and cover crops is intricately linked with carbon buildup in soil systems. Long-term studies indicate that composts or manures enhance soil carbon storage, contrasting with synthetic fertilizers that may lead to carbon loss. Synthetic nitrogen sources contribute to greenhouse gas emissions and soil acidification. When compost replaces synthetic nitrogen, increased root growth sequesters atmospheric carbon. Regenerative systems, with nitrogen-fixing legumes or trees, negate the need for synthetic fertilization, promoting carbon storage and reducing environmental damage. Fungi, particularly mycorrhizal fungi, crucial for nutrient cycling and soil structure, play a pivotal role in soil carbon sequestration by creating stable aggregates that protect soil carbon from being lost (Allen, 2007). Strategies like perennial plantings and reduced tillage that encourage mycorrhizal fungi partnerships contribute to the long-term stabilization of soil carbon.

Grazing Management

Regenerative grazing, including management-intensive approaches like adaptive multi-paddock (AMP) grazing and holistic grazing, enhances carbon sequestration in grazing lands, offsetting greenhouse gas emissions from livestock. With calculated herd movement, these systems mimic natural patterns, allowing forage recovery and soil organic carbon increase. Integrated into crop-livestock systems, regenerative grazing offers additional benefits, including improved soil health, reduced methane emissions, and enhanced carbon storage, surpassing some climate mitigation policies.

Conclusion

Regenerative Agriculture emerges as a holistic and convergent approach, addressing environmental, social, and economic dimensions of sustainable food production. Guided by principles like minimizing soil disturbance and integrating livestock, RA practices such as cover cropping, no-till, and regenerative grazing offer effective solutions to combat climate change, enhance soil health, and promote sustainable agriculture. Stakeholder collaborations and policy implementations are crucial for widespread adoption and success.

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Remote Sensing and GIS for Digital Agriculture

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Digital agriculture aka digital farming integrates advanced technologies like satellite and aerial remote sensing, precision agriculture tools, Internet of Things (IoT) sensors, big data, artificial intelligence, and machine learning, into a single system that enables farmers and other stakeholders within the agriculture value chain to improve food production. Unlike conventional farming, a digital agriculture system collects data more frequently and accurately and analyzes and interprets to make better-informed decisions. Further, the decisions can be quickly implemented with greater accuracy through robotics and advanced machinery. Digital agriculture has a critical advantage of making use of resources more efficiently, gender-neutral and therefore, making agriculture more productive and sustainable. It also allows for larger data and information sharing and replicability in other areas.

The application of remote sensing in agriculture has led to a revolutionized approach called 'precision agriculture' since the 1980s. This approach is based on the integration of global positioning system (GPS), geographic information system (GIS) and remote sensing technologies, which are collectively known as 'Geoinformatics'. Remote sensing has transformed the way we manage our natural resources. Nowadays, there are over a thousand active remote sensing satellites orbiting Earth, equipped with various sensors that collect observation data from the earth's surface, including land, water, and atmosphere. Data science and big data analytics have gradually merged into precision agricultural schemes, enabling the data to be analyzed quickly for decision making.

With the rapid development of remote sensing technology, especially the use of new sensors with higher resolutions, the volume of remote sensing data will dramatically increase with much higher complexity. Remote sensing data for agricultural use come in different forms, acquired from different sensors, at different intervals, and scales. However, the question remains as to how to manipulate and convert the big data to 'small' sets for specific issues or fields for precision agricultural operation. The acquisition, processing, storage, analysis, and visualization of these big data are critical to the success of digital agriculture.

Remote sensing data needs to be processed before use. Raw images acquired from remote sensors on satellites and aircraft must be corrected due to deformations from interactions between sensors, atmospheric conditions, and terrain profiles. Corrections typically include radiometric and geometric corrections. The raw and corrected remote sensing images can be summarized into data products at different levels. Several data products, however, are currently available at different levels. These are summarized in Table 1. In recent years, there has been significant progress in airborne remote sensing, particularly in the use of UAV-based remote sensing techniques, to monitor natural resources and manage agricultural lands. With the advances in remote sensing systems and processing methods, it is now possible to formulate more detailed remote sensing data product systems that can be used for processing airborne remote sensing data.

Table 1. Currently available satellite data products

Level	Product description
0	Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communication artifacts (e.g., synchronization frames, communications headers, duplicate data) removed
1A	Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e.g., platform ephemeris) computed and appended but not applied to the Level 0 data (or if applied, in a manner that Level 0 is fully recoverable from Level 1A data)
1B	Level 1A data that have been processed to sensor units (e.g., radar backscatter cross section, brightness temperature, optical etc.); not all instruments have Level 1B data; Level 0 data are not recoverable from Level 1B data
2	Derived agro-geophysical variables (e.g., ocean wave height, ice concentration, soil moisture/ temperature, canopy temperature, etc.) at the same resolution and locations as Level 1A source data
3	Variables mapped on uniform spatial grid scales, usually with some completeness and consistency (e.g., missing points interpolated, complete regions mosaicked together from multiple orbits, etc.)
4	Model out or results from analyses of lower level data (i.e., variables that were not measured by the instruments but instead are derived from these measurements)

Source: Huang *et al*. (2018)

As remote sensing technology develops, and high-resolution data becomes available, traditional pixel-based classification methods may not be sufficient for practical needs. This is because high-resolution images with more details may be classified into unknown "blank" spots, which can have a negative impact on later analysis. Object-based remote sensing image classification provides a solution by segmenting the image to merge neighboring pixels with similar spectral signatures into objects to classify. Physically based model simulation and parameter inverse are being researched to understand the interaction between remote sensing and ground surface features. In recent years, deep learning has been developed for remote sensing image classification. It has been strongly believed that deep learning techniques are crucial and important in remote sensing data analysis, particularly for the age of remote sensing big data.

Visualization of remote sensing data and products is critical for users to interpret and analyze. GIS, as a platform for remote sensing data visualization, has developed in four areas over the last decade: modularization, web enabling, miniaturization and mobility, and data based. Modular GIS is organized with certain standards and protocols, while web GIS has been developed to publish geospatial data for users to view, query and analyze through the Internet. Although desktop GIS applications still dominate, mobile GIS clients have been adopted with personal digital assistants (PDA), tablets, and smartphones. Spatial data management in GIS has also developed from flat file management, file/database management, to spatial database management. Spatial data management provides the capabilities of massive data management, multi-user concurrent operation, data visit permission management, and concurrent visit and systematic applicability of database clusters.

Remote sensing and GIS offer unique opportunities to develop digital agriculture. There are many examples of their applications in digital agriculture. A few are illustrated here.

Digital soil mapping

Digital soil mapping (DSM) is a revolutionary technique that helps us to understand and manage soil, which is a crucial resource that we often overlook. By utilizing the potential of remote sensing data and advanced statistical models, DSM provides a data-driven method to map soil properties and types. It offers valuable insights into this multifaceted and essential ecosystem component that would otherwise be difficult to obtain.

Traditional soil mapping methods are time-consuming and expensive. Remote sensing offers a powerful tool for digital soil mapping (DSM), where satellites, airplanes, and drones capture electromagnetic radiation reflected from the Earth's surface to provide valuable insights into various environmental features. DSM focuses on spectral reflectance, which is the way different soil components interact with light at various wavelengths. DSM offers a key role in precision agriculture, soil and land use mapping, carbon sequestration, soil nutrient assessment and in many other applications.

Spectral indices, which are mathematical combinations of specific wavelengths, can be used to predict important soil properties like organic matter content, texture (sand, silt, clay), and moisture. This type of data allows for detailed mapping of these properties across large areas with high spatial resolution. Different soil types have unique spectral signatures that enable their identification and mapping, even in areas with limited field data. This information is crucial for effective land management practices such as crop suitability mapping. Satellites like Sentinel-2 can provide time-series data that allows for tracking changes in soil properties over time. This is essential for monitoring soil degradation, erosion, and the impact of agricultural practices.

However, soil properties are complex and influenced by various factors beyond their inherent composition, which can make it difficult to accurately interpret spectral signatures. Extracting meaningful information from raw spectral data requires advanced statistical and machine learning techniques, as well as expertise and computational resources. Proper ground validation is also necessary. While remote sensing offers vast spatial coverage, field data collection remains essential for validating and calibrating predictions to ensure accuracy and reliability. Despite these challenges, the potential of remote sensing data for DSM is enormous. With advancements in sensor technology, data processing algorithms, and open-source platforms, its accessibility and accuracy are continuously improving.

Case study 1: Digital soil map of India

Mapping soil resources at a national scale in large countries like India is challenging due to limited soil data available and the efforts required to collect them. The first digital map of essential soil properties down to a depth of 2 m across India was developed by Reddy *et al*. (2021) by using legacy soil information (Fig. 1). The authors collated a legacy database containing analytical data for 1,707 soil profiles with 7,337 soil horizons from reports published by the National Bureau of Soil Survey and Land Use Planning and other Indian organizations. They used 3D regression kriging based on the random forest model to map sand and clay contents, pH, and soil organic carbon (SOC) contents at depths as per the GlobalSoilMap specifications. Important covariates included mean monthly temperature and precipitation data from the World Climatic Centre and terrain attributes derived from NASA's Shuttle Radar Topography Mission (SRTM) digital elevation model. Elevation, topographic wetness index, high rainfall, and temperature were identified as the major drivers for the variability of soil properties. Although finer soil fractions are considered major drivers of SOC stabilization, rainfall during June (onset of monsoon) was a significant climatic driver for SOC in Indian soils. The national maps of soil properties can be linked to soil productivity and provisioning of ecosystem services to guide policymakers in creating region-specific soil management plans.

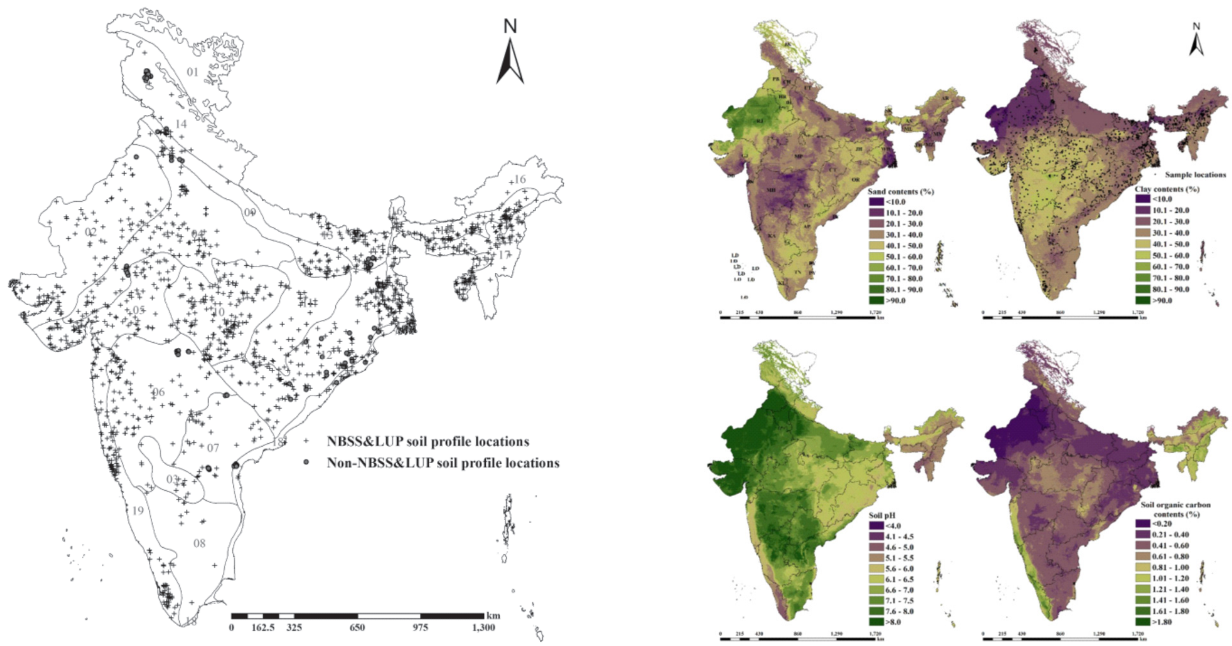

Figure 1. (a) Map showing locations for soil profiles and boundaries of the agroecological regions (AER) within India (numbers indicate the specific AER); and (b) Sand, clay pH and SOC contents of 0–30 cm layer [Source: Reddy *et al*., 2021]

Land use/ land cover change and crop yield forecasting

Advances in sensor technology, data processing algorithms, and machine learning have made remote sensing more accessible, affordable, and accurate. With the continued evolution of these technologies, we have several groundbreaking applications leading to a more sustainable and productive agriculture.

Case study 2: Land use/land cover change map of India

India has experienced significant changes in land use and land cover due to population growth and economic development in recent decades. To measure the impact of these changes at regional and global scales, predict future changes and support planning decisions, a regional land use change model based on district-level inventory data has been used to create an annual time series of high-resolution gridded land use and land cover maps for the Indian subcontinent between 1960 to 2010 (Fig. 2). The analysis was based on the connection between present-day land use and land cover and various spatially explicit covariates. However, when simulated map for 1985 was compared with the remotely sensed land use/cover maps for 1985 and 2005, a significant discrepancy was recorded. This could be due to the differences in the amount of land use/cover change between the inventory data and the remote sensing maps.

Case study 3: Field scale spatial wheat yield forecasting

Accurately forecasting crop yields in advance is crucial for numerous applications. A study utilized minimal field input data to predict crop yields well ahead of harvest at the field level by assimilating remote sensing derived crop parameters and weather forecasts into the InfoCrop-Wheat crop simulation model (Dhakar *et al*., 2022; Fig. 3). The crop simulation model was calibrated and

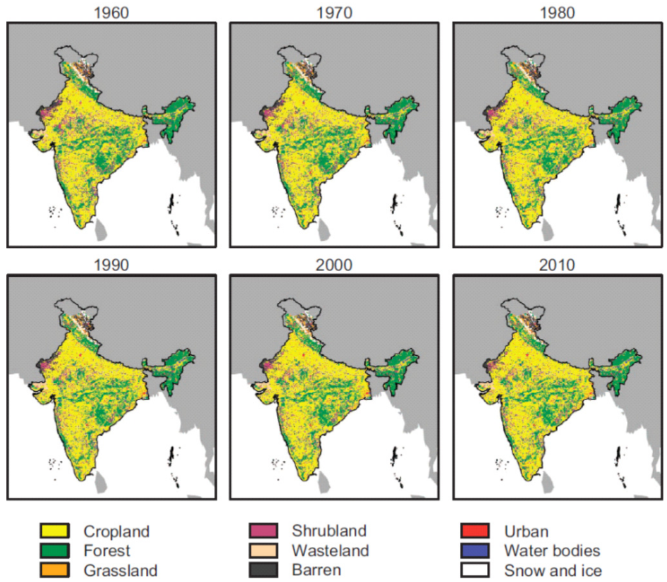

Figure 2. Simulated land use/land cover maps at decadal time steps across India [*Source:* Moulds *et al.*, 2018]

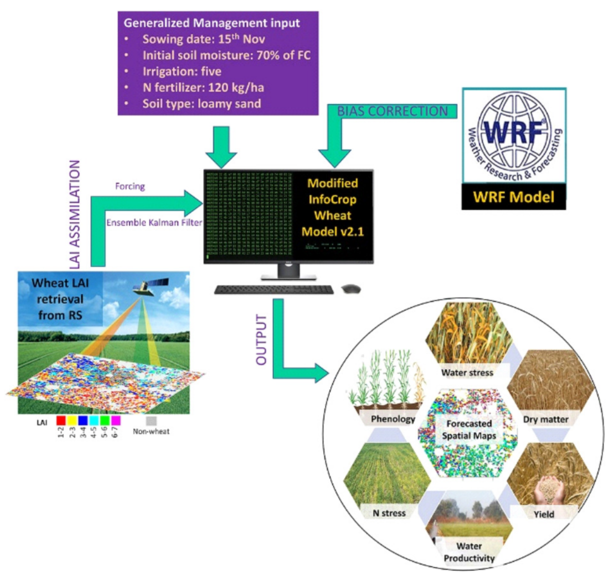

Figure 3. A scheme of wheat yield forecasting by integrating crop simulation model with weather forecast and satellite remote sensing [Dhakar *et al.*, 2022]

validated at both research farms and farmers' fields. The crop leaf area index was retrieved through inversion of the PROSAIL radiative transfer model from Sentinel-2A and Landsat-8 images and validated using in-situ leaf area index measurements. The simulation model was modified to test the assimilation of remote sensing derived leaf area index. A workable prototype of a field-scale wheat growth and yield forecasting system was developed which demonstrated acceptable accuracy in forecasting phenology, dry matter, and yield of wheat at the field scale when weighted adaptive bias-correction of weather forecast was incorporated with a 15-day lead time. The prototype may be further scaled-up for predicting real-time crop condition and yield losses at farmers' fields.

Plant phenomics

There is a pressing need for significant improvements in crop yield to keep up with the growing population and changing climate. Although the advances in genomics have greatly benefited plant breeding, profiling the crop phenome (i.e., the structure and function of plants) associated with allelic variants and environments remains a major technical hurdle.

Case study 4: Phenomics based plant biomass prediction

A state-of-art spatial and temporal phenotyping facility was established in 2017 at ICAR-IARI, New Delhi. This facility was used to identify a consistent model to predict biomass, RGB and NIR images of wheat germplasm and Recombinant Inbred Lines (RILs) of Raj3765xHD2329 were recorded to predict biomass and leaf area (Singh *et al.*, 2023) Researchers used 16 machine learning models for two consecutive years of experiments to predict different fresh weight, dry weight, and shoot area (Fig. 4). Different architectural and physiological traits were identified as determinants of biomass accumulation. Identifying the genetic basis of major determinants of biomass accumulation was possible.

Figure 4. (A) Nanaji Deshmukh Plant Phenomics Center (NDPPC) at ICAR-IARI; facilities like (B) climate controlled greenhouses; (C) experiment for non-invasive biomass prediction; (D) image acquisition and processing; (E) RGB, side view image of wheat plant inside imaging chamber; and (F) Destructive sampling for biomass measurement

Conclusions

Digital agriculture is transforming the way we cultivate crops. It utilizes a variety of digital technologies such as sensors, drones, robotics, and big data to enhance efficiency, productivity, and sustainability in agriculture. This has led to several unique applications, such as providing farmers with real-time information on soil moisture, crop health, and pest infestations, allowing for precise interventions with fertilizers, irrigation, and pest control. Drones can capture images of farms, identifying optimal planting areas and diagnosing potential problems before they become visible. Robotics can perform farm operations like weeding and harvesting. Remote sensing provides data about the Earth's surface, while GIS analyzes and visualizes that data to reveal patterns and support informed decision-making. Both these tools have evolved into multidisciplinary science disciplines and together contribute immensely to digital farming.

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Alternative Source of Phosphatic Fertilizer: Opportunity and Perspectives

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Agriculture is the mainstay of the Indian economy. Fertilizers plays a key role in agricultural production that relies on the use of inorganic fertilizers and ensures food security of the country. The production of food grains in India touched a record level of 330.5 million tonnes (Mt) in 2022-23 (FAI, 2023). This increased in food production is concomitant to the increased consumption of fertilizers. Presently, consumption of total fertilizer nutrients ($N+P_2O_5+K_2O$) in India is estimated at 29.84 million tonnes (Mt) during 2022-23, and registered a marginal growth of 0.2% over 2021-22 (FAI, 2023). While, consumption of N and P_2O_5 recorded increase of 4% and 1.2%, respectively, over 2021-22, consumption of K_2O showed a sharp decline of 32.2%. These nutrients are supplied by conventional chemical fertilizers such as urea, diammonium phosphate (DAP), single superphosphate (SSP), complex fertilizers (NP/NPK/NPKS), and muriate of potash (MOP). India is import dependent to a great extent to meet its fertilizer demand either through import of finished products or raw materials. Further, because of volatile international market and steep rise in prices of raw materials required for production of finished products, the cost of fertilizers has increased sharply. This necessitates to find out the potentiality of the alternative sources of nutrients to supplement nutrient requirement of crops and to reduce the cost of crop production. Further, indiscriminate and imbalanced use of fertilizers without or little amount of organic manures addition lead to soil degradation and environment which will adversely affect crop productivity and in turn food security of the nation. Therefore, it is necessary to achieve higher food production in future with lesser or same quantity of inputs through other means. To protect the soil health and sustainable crop production, two approaches can be adopted namely, (a) increase the nutrient use efficiency of conventional fertilizers so that more nutrients are taken up by the crop and less are lost to environment thus meeting increased demand for nutrients without increasing dosage; and (b) replace or supplement conventional fertilizers with alternative fertilizers which provide the soil with nutrients while preserving soil health. Under such circumstances, utilization of alternative sources of nutrients provides an opportunity to reduce the import of costly fertilizers.

In modern agriculture, bioavailability of phosphorus (P) has been identified as a bottleneck in the sustainable agricultural production. Phosphorus is the 11th most abundant element on the earth crust and total P content is quite abundant in many soils, but due to its low bioavailability, it is frequently limiting nutrient in agricultural soil. High demand of commercial P-fertilizer results in depletion of good quality rock phosphate (RP) reserves across the globe and it is one of the major challenges to maintain P-fertilizer supply in developing countries, particularly in India. The RP deposits suitable for commercial production of P-fertilizer are limited. On the other hand, the use efficiency of soluble P-fertilizer is very low (<20%) in most of the soils. Considering the above factors, there is a need to have an economically viable and sustainable supply of P from indigenous RP sources. Use of low-grade RP through partial acidulation, thermally promoted, and mixing with pyrites have been tried earlier as an alternative source of P-fertilizer for crop growth (Biswas and Narayanasamy 2006). However, they were found less effective compared to water soluble P-fertilizers like SSP and DAP. In this article, we discussed the various options of value addition of indigenously available low-grade RP for sustainable farming through biological interventions including use of phosphate solubilizing microorganisms (PSM) and composting techniques. Integrated strategies and recent novel technological interventions to increase P availability from indigenous low-grade RP were also discussed.

Low-grade Indian rock phosphate

The demand of P is met essentially from rock phosphate (RP) across the globe. According to available data, the recoverable global RP reserves of all types and grades are estimated to be ~60,000 million tonnes (Mt) (van Kauwenbergh, 2010). However, most of world's production of RP is confined to few countries namely, Morocco and other African countries, USA, Near East and China. Meanwhile, ~90% of the total RP reserves mined at present is used for fertilizers production (FAO, 2015). The scenario of reserves of RP in India is, however, not very comfortable as it possesses a resource of only 311 Mt (0.2% of the world reserve) of RP of all types and grades (Indian Bureau of Mines, 2021). The important reserves of RP mined in India are Jhabua from Madhya Pradesh State Mining Corporation Ltd., Meghnagar, Madhya Pradesh; Purulia from West Bengal Mineral Development and Trading Corporation Ltd., Purulia, West Bengal; and Udaipur from Rajasthan State Mines and Minerals Ltd., Udaipur, Rajasthan (Biswas and Narayanasamy, 2006). Out of the total RP resources, the country has a predominance of low-grade RP, and only 9% of the total RP reserves are suitable (containing >30% P_2O_5) for commercial P-fertilizer production (Indian Bureau of Mines, 2021). These low-grade RP is unacceptable to P-fertilizer industry due to its very low P content (<25% P_2O_5) and high $CaCO_3$ content (Narayanasamy and Biswas 1998; Biswas and Narayanasamy, 2006). There is a need to develop technology for utilization of this natural P source in agriculture (Roy *et al.*, 2015; Basak and Biswas, 2016). The feasibility of RP for direct use in agriculture depends on the rate of dissolution which is determined by its chemical composition as well as type of soils and crops grown therein. This might also be due to the fact that finer the particle size, the greater the degree of contact between RP and soil, thereby, greater the rate of dissolution. Different sources of RP in the world can thus be compared using relative solubility indices (Hammond *et al.*, 1986) and ranked them accordingly for their relative agronomic potential as alternate P source.

Alternative use of low-grade RP through biological interventions

The agronomic effectiveness of direct application of indigenous RP in acid soil is very common, particularly in tea gardens and plantation crops. However, as source of P in neutral to alkaline soils has been found less effective compared to water soluble P-fertilizers (Narayanasamy and Biswas, 1998). Thus, some interventions are needed to speed up the P release rate. Biological intervention involving some bio-agents is one of the cost effective means of solubilization or mobilization of RP and subsequent release of P in the process for the specific purpose. In order to improve P availability from RK, different bio-agent (plants and microbes) and biological process (composting) may be employed as means of supplying P for plant nutrition.

Improving availability of RP through phosphate solubilizing microorganisms

Phosphate biofertilizers are widely used in agriculture for improving P mobilization in soil. There are well known microbial species, including bacteria and fungi capable of solubilization and mobilization of P from insoluble minerals. Phosphate solubilizing microbes (PSMs) are a group of beneficial microorganisms capable of hydrolyzing organic and inorganic P compounds from insoluble compounds. Among the important PSMs, phosphate solubilizing bacteria (PSB) such as *Bacillus*, *Pseudomonas*, and *Rhizobium;* phosphate solubilizing fungi (PSF), such as *Penicillium* and *Aspergillus*; actinomycetes, and arbuscular mycorrhiza are notable. In general, bacterial strains are more effective in P-solubilization than fungi. The phosphate biofertilizers are quite promising in developing countries where it is used to mobilize native soil P due to high cost of commercial P-fertilizer. In this way, phosphate biofertilizers play an important role in the transformation of native soil P into bioavailable form for plant uptake (Alam *et al.*, 2022, 2023). Many recent studies indicate that treatment of soil as well as phosphate minerals with PSM significantly enhances P bioavailability and plant growth (Biswas, 2021). Study revealed that low-grade RP inoculated with PSB can supplement commercial P-fertilizer in sub-tropical Inceptisol for wheat production (Biswas *et al.*, 2022a, b). It is also found that RP inoculated with PSB can be recommended to grow wheat, as it can maintain better and steady supply of P to the crop and synchronize P supply with crop demand, by improving soil P fertility, biological health and reducing P fixation by soil. These findings concluded that RP inoculated with PSB could supplement 50% P-fertilizer for growing wheat in Inceptisol, with the added advantage to exert potential beneficial residual effect to the next rice crop on the same soil without addition of P.

Improving availability of RP through composting

With the emerging concern on large quantity of the agricultural waste being produced, the concept of waste management becomes one of the key focuses of sustainable agricultural development. Thus, the appropriate management of agricultural wastes assumes a great significance. One of the alternative options of utilization of these large quantities of nutrient rich agricultural wastes is by converting them into value added product like compost and recycle them back to the field which have drawn the attention of scientists to reduce environmental pollution and increase efficiency of carbon and nutrient rich inputs for higher productivity. Preparation of enriched compost using crop residues and low-grade RP sustains cropping system through better nutrient recycling and improvement of soil physical properties. Development of alternative fertilizer material like enrichment of organic manures through minerals and their effect on crop productivity and soil fertility build-up has great potential which will give the benefits of applying an organic as well as inorganic for increasing crop production and maintaining soil quality. Composting of organic matter with rocks and minerals can release nutrients and improve the P availability of the system (Table 1).

Composting of organic matter (crop residues and animal manures) with RP is well known to increase P dissolution (Nishanth and Biswas, 2008; Biswas, 2011; Moharana and Biswas, 2016; Reza *et al.*, 2017). Mineral structure could be disintegrated during the composting process and rendered more available P for plant nutrition. The basic principle underlying the composting of RP with organic matter is due to production of organic acids such as oxalic, citric, malic, acetic, *etc.* as a result of their decomposition. Release of these acids creates a localized high acidity in the immediate vicinity of RP and some organic acids even leads to complexation of calcium (Biswas *et al.*, 2009; Basak, 2019a, b). These organic acids are actually low molecular weight and characterized by the possession of one or more carboxyl groups. Depending on their dissociation properties and number of carboxylic groups they possess, organic acids carry varying negative charges. This negative charges allow the complexation of metal cations in solution and displacement of anions from the soil matrix (Basak, 2017). Phosphate dissolution rates can be greatly accelerated during composting in presence of organic acids such as oxalic, citric, malic, *etc.* leading to 10-1000 folds higher P release

Table 1. Mobilization of P and K from insoluble minerals through composting process

Mineral	Organic material	Outcome	Reference
Francolite and rock phosphate	Poultry manure	20% francolite and 27% rock phosphate dissolved	Mahimairaja *et al*. (1994)
Rock phosphate	Rice straw and fresh cow dung	Significant P mobilization from RP	Biswas and Narayanasamy (2006); Biswas *et al*. (2009); Meena and Biswas (2014a, b)
Rock phosphate	Rice straw and FYM	Increased available P content in final product	Hellal *et al.* (2012)
Rock phosphate	Sheep dung and leaf compost	Available P content increased in final product	Adhami *et al*. (2014)
Rock phosphate	Press mud	Available P content significantly improved in the mature compost	Reza *et al*. (2017)
Rock phosphate	Isabgol straw and fresh cow dung slurry	Significant improvement in available P in final product	Basak (2017)

than normal P release from RP. Moreover, significant amount of CO_2 evolution during composting process renders low pH environment and accelerates the P release from mineral structure (Biswas *et al*., 2009; Basak and Gajbhiye, 2018; Basak and Saha, 2022).

Rock phosphate based formulations

Novel P-fertilizer product using organic acid loaded NCPC with RP and PSB

Organic acid loaded nanoclay polymer composite (NCPC) is one of the promising approaches for solubilization of low-grade RP (Biswas, 2021). Roy *et al*. (2018) prepared a novel product using organic acid (oxalic and citric acid) loaded NCPC with low-grade Indian RPs such as Udaipur RP (Udaipur, Rajasthan) and Purulia RP (Purulia, West Bengal), and PSB (*Pseudomonas striata*) for improving P solubilization from RP. The hypothesis of this novel product is to solubilize low-grade RP through organic acids loaded NCPC and PSB which, in turn, release P slowly synchronizing crop demand for P. The application of RP by loading NCPC enhances residence time of citric acid in soil, and results in higher solubility of P from the RP. Also, these RP contains significant amount of citrate soluble P which solubilizes over the period of time and becomes available to crops. In another study, it was observed that organic acid based low-grade RP formulation effectively supplemented 50% dose of P-fertilizer for growing wheat (Biswas *et al.,* 2022a, b). It also improves soil P fertility and biological properties such as dehydrogenase, acid phosphatase and alkaline phosphatase activities in an Alfisol (Biswas *et al.,* 2023). Effective bio-mineral formulation developed from low-grade RP may also found promising approach through which faster and uninterrupted supply of P according to the crop demand may be given (Maity *et al*., 2022). These researches showed that through this avenue low-grade RP could be exploited by converting them to novel product using low-molecular weight organic acids along with PSB which acts as slow release fertilizer to synchronize P release with crop demand and potentiality of this product as a promising alternate P source amidst P scarcity. Thus, it has great scope for its production and adoption as P-fertilizer and save the costly input and reduce the dependence on imported RPs and mineral acids, and prove as a potential green and sustainable technology to meet the P fertilizer demand in agriculture. However, such bio-mineral fertilizer comprising of low-grade RP and PSM has to be studied extensively as a potential source of P in agriculture.

Polymer coated novel controlled release RP formulations

Novel product of polymer coated controlled release RP formulations have been synthesized by partially acidulating RP with sulphuric and phosphoric acids followed by coating with polyvinyl alcohol and liquid paraffin @ 2 and 3% levels of coating as promising slow release P-fertilizer for improving P use efficiency by crops (Sarkar *et al*., 2018, 2020). These products were found to release P for a longer period compared to water soluble P-fertilizer like DAP, thereby supply P gradually for a longer period of crop growth as evident from greater biomass yield, P uptake and recovery by wheat in a P-deficient Typic Haplustept. Thus, commercial exploitation of this product would prove highly beneficial to reduce the quantity of fertilizers to be applied, thereby save input costs as well as environmental consequences.

Opportunities and Perspectives

Decline in good quality rock phosphate and increasing cost of raw materials for manufacturing commercial P-fertilizer the major constrains of sustainable agricultural production in many parts of the world and India in particular. Under such circumstances, utilization of low-grade RP is inevitable for supplying of P to sustain agricultural production. Encouraging results have been observed from the existing literature regarding application of low-grade RP and their value added products developed through chemical and biological means to supplement commercial P-fertilizers in agriculture. There are many promising approaches that can effectively supply P from low-grade RP at a sufficient rate to meet the crop demand. The strategies like, composting and microbial intervention, NCPC and organic acid based formulations, and bio-mineral formulations are found promising in improving P availability. All these approaches need a careful chemical and biological interventions to speed up the nutrient release from insoluble sources like low-grade RP. Utilization of locally available low-grade RP and bio-resource with best possible combination should be given more emphasis to improve P supplying capacity of crops. However, these technologies to be evaluated under different field trials with different crops under diverse agro-climatic conditions.

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Use of Modern Tools and Techniques in Soil Physics Research to Meet the Challenges for Sustainable Agri-food System and Environmental Protection

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ABSTRACT

Sustainable intensification of agri-food system in the face of land degradation, soil health deterioration, environmental pollution and decline in factor productivity is a major challenge in these days. Ensuring good soil health is indispensable for sustaining the agricultural productivity at higher level. Soil physicists would play a major role in addressing this challenge and restoring the agroecosystem. Generally, soil physics aims at the proper management of soil by means of irrigation, drainage, soil and water conservation, tillage, aeration, and the regulation of soil temperature. It also considers the response of soil bodies to mechanical stresses and the fate of various solutes in the soil and also mitigating the environmental pollution. There is a need for reorientation of soil physics research under changing climate, land degradation, declining factor productivity besides environmental pollution. There are some unsolved thematic areas of soil physics research and the solutions for which should be attempted in a multidisciplinary mode. Recent advances in the use of measurement tools, improved understanding of soil physical processes and modelling and use of modern tools and techniques like artificial intelligence (AI) and machine learning (ML) would assist in solving these problems for achieving sustainable intensification of agri-food system.

Key words: Soil Physics, Modelling, AI/ml, Soil health, Ecosystem services

Introduction

Sustainable agriculture aims at meeting the needs of present generation without endangering the resource base of the future generation. Agricultural sustainability depends on maintaining environmental quality, economic viability, technical feasibility and social replicability. Unfortunately, unsustainable productivity, yield decline, environmental pollution, decreasing soil organic matter storage, degradation of soil health, decreasing factor productivity under high intensity agriculture in the post green revolution era and climate change has been a matter of great concern in the recent days. So, to sustain the productivity at higher level is the key issue in agriculture to meet the increasing demands of food and fibre for the growing population. Maintaining soil health is indispensable for sustaining the agricultural productivity at higher level. The term soil health and soil quality are often used interchangeably in the scientific literature. Soil quality is defined as the capacity of soil to function within ecosystem and land use boundaries, to sustain biological productivity, maintain the environmental quality and promote plant, animal and human health (Doran and Parkin, 1994). Soil quality includes three groups of mutually interactive attributes *i.e.,* soil physical, chemical and biological quality, which must be restored at its optimum to sustain productivity at higher levels in the long run. Thus, it is high time to appreciate the fact that unless the soil physical environment is maintained at its optimum level, the genetic yield potential of a crop cannot be realized even when all the other requirements are fulfilled as it influences the soil chemical and biological qualities also. The environmental consciousness of general public is harping on appropriate farm management practices to protect water, air and soil quality while staying economically profitable. At the same time, market based global competition in agricultural production and the global climate change are challenging the economic viability of the traditional agricultural systems, which necessitates development of a new and dynamic production systems. Site-specific optimal management of spatially variable soil, appropriately selected crops, and available water resources on the landscape can help achieve both environmental and production objectives. The sustainable management of soil ecosystem is fundamental to global food, water, and energy security, especially under increasingly unpredictable weather patterns, caused by climate change. The land-water-food-climate nexus is ultimately central to sustainable development, whereas the soil inextricably links these critical domains (Keith *et al*., 2016). Stakeholders and decision makers in all four domains are necessarily focussing on the effects of soil degradation on climate change, water resource management and food production are key to the development of sustainable agricultural practices and policies (Wang *et al*., 2023). So, to meet the challenges of sustainable agri-food system and environmental protection soil physics can play a significant role.

Soil physics discipline and its relevance

Soil physics may be defined as the application of the principles of physics to the characterization of soil properties and the understanding of soil processes, especially those involving the transport of matter or energy (Sposito and Reginato, 1992). This definition implies that soil physics is a sub-discipline of both physics and soil science. So, Soil physics is the branch of soil science dealing with the physical properties of the soil, as well as with the measurement, prediction, and control of the physical processes taking place in and within the soil (Hillel, 1998). Just as physics in general deals with the forms and interactions of matter and energy, soil physics deals specifically with the state and movement of matter and with the transformations and fluxes of energy in the soil. German scientists Schübler, Schumacher, and Wollny were among the first to study soil physical properties for crop production in the nineteenth century. Wollny studied the effects of plant growth and soil management on soil physical properties and was founder of first soil physics journals ('Forschungen auf demGebieteAgrikulturphysik' 1878-1898), and is therefore considered by many to be the father of soil physics in Europe.

The fundamental study of soil physics aims at understanding the mechanisms governing the behavior of the soil and its role in the biosphere, including such interrelated processes as the terrestrial energy exchange and the cycles of water and transportable materials in the field. On the other hand, the practice of soil physics aims at the proper management of soil by means of irrigation, drainage, soil and water conservation, tillage, aeration, and the regulation of soil temperature, as well as the response of soil to mechanical stresses and the fate of various solutes in the soil. Soil physics is thus both a basic and an applied science with a very wide range of interests, some of which are shared by other branches of soil science and by such interrelated sciences as geology, terrestrial ecology, hydrology, microclimatology, sedimentology, botany and agronomy. Soil physics is also closely related to the engineering profession of soil mechanics, which deals with the soil as a construction and support material.

Soil physicists in the beginning were interested primarily in the agricultural aspects of their discipline, hence their research focused on the soil as a medium for the production of crops (including tillage and improvement of soil structure, moisture conservation in rainfed farming, and optimal management of irrigation and drainage). Recent decades have witnessed an increasing emphasis on the environmental aspects and applications of soil physics. Consequently, research in soil physics has expanded its scope to include problems related to natural ecosystems and to processes affecting the chemical pollution of the environment. Processes occurring in the soil are now seen to affect much more than the on-farm production of crops. Different soil processes affect the entire terrestrial environment, including the local and regional climate, the natural food chain, biodiversity and the fate of numerous waste products of our civilization (among which are numerous pathogenic and toxic agents). Increasingly, the main concern of soil physics has shifted from the laboratory to the field and from a one-dimensional to a multi-dimensional view interfacing with the domains of sister disciplines such as meteorology and climatology, hydrology, ecology, and geochemistry. The larger domain of soil physics encompasses greater complexity and variability in space and time, the treatment of which requires reliance on stochastic as well as deterministic methods.

Knowledge of soil physics has great implications on the ecosystem as depicted in Fig.1.

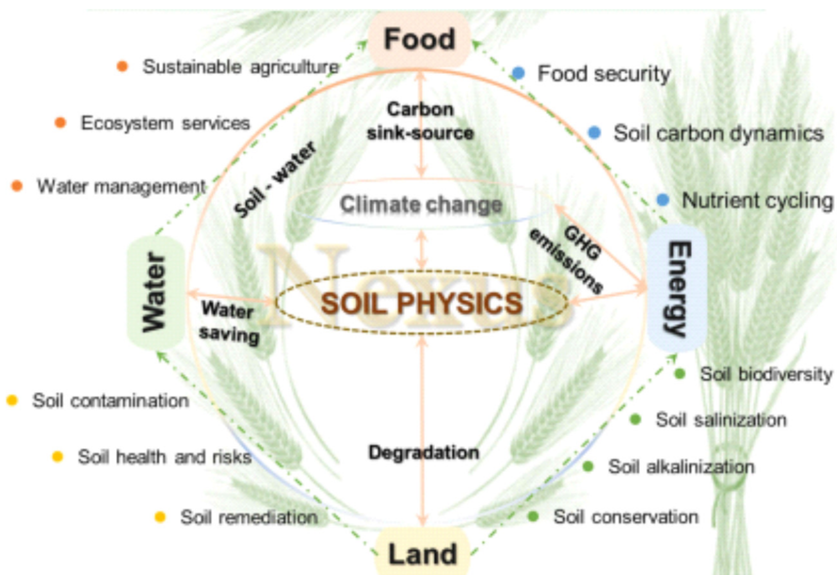

Figure 1. Applications of Soil Physics in ecosystems (*Source:* Wang *et al.*, 2023)

Recent challenges of soil physics research

Considering the complexity of the problems faced these days with respect to sustainability of the agri-food system and environmental protection and the role of soil physicists to solve these problems, following challenges has been identified in soil physics research by a group of soil physicists (Jury *et al.*, 2011)

1. Characterizing the transport properties in field soils

1.1 Development of Scaling relations

The soil properties that influence the dynamics and pathways of water and chemicals are difficult and time consuming to measure. Moreover, they vary considerably in space even across small distances in the natural environment. Our flow and transport models often require area or volume averaged estimates of these properties, yet the number of samples necessary to calculate meaningful averages at the field scale is often prohibitively large. Scaling relations were developed as a means to circumvent the measurement problem and to enable comparisons between similar systems by using one or more easily measured or estimated parameters to describe the differences in soil geometry from one region of soil to the other. These parameters are then related to transport and retention properties through theoretical or empirical relationships, thereby allowing a set of properties measured at a given location to be extended to other regions via the regions' scaling factors.

1.2 Defining Effective properties

An effective property is a functional relationship between volume-averaged quantities and is scale and model dependent. Hydraulic functions measured at the core or plot scale are notoriously variable in natural soil, with properties such as infiltration rate ranging across several orders of magnitude within a typical field (Sharma *et al.*, 1980). Because the information required to create a continuous map of the variability of these properties is unobtainable, plot and field scale models of infiltration, soil water movement, and solute transport generally use average or "effective" soil hydraulic properties to represent the processes. We need to extend the concept of effective properties to layered soils having vertical as well as horizontal variability. It may be possible that in most cases infiltration is restricted to the top 30 cm and that the properties of the topsoil control infiltration and thus alone can define the effective properties. This simplification is unlikely to work for redistribution, however, and it may be necessary to use the arithmetic or geometric mean properties of the combined layers to define the effective properties.

1.3 Relating soil structure and functions

Spatial organization in soils, usually referred to as soil structure, is present at all scales and its influence on hydrologic processes is also scale dependent. At the pore or aggregate scale, soil structure is defined by the arrangement of minerals and organic matter in combination with biological components. At the horizon or pedon scale, soil structure appears as soil horizons and peds, which influence the retention and transport of infiltrating water and solutes, especially as preferential flow (Lin *et al.*, 1999). At the field or hillslope scale, surface cover features control storage and partitioning between runoff and infiltration, thereby affecting groundwater recharge and ecosystem water (Zehe and Flühler, 2001). Finally, at the watershed or basin scale, the spatial organization of soil types and associations along with the parent material provide information on soil cover structure, while soil–atmosphere interactions and feedbacks characterize the soil hydraulic functions emerging at this scale (Vereecken *et al.*, 2010a).

Very little is known about how structure changes with time. We have some understanding of the effects of tillage and natural reconsolidation on the changes in soil hydraulic properties (Ahuja *et al.*, 1998). However, we need to know much more about dynamic changes in void space in various structural units to be able to interpolate and extrapolate structure–function relationships in soil hydrology with time. Such temporal projections are needed to understand the changes in soil hydrology due to soil management and due to changes in ecosystems undergoing ecological succession or affected by climate change. Modelling soil structural changes under different management practices is a great challenge.

2. Deviations from surface tension-viscous flow

2.1. Unstable water flow in soils

Research during the last half century has advanced our understanding of the conditions necessary for the onset of unstable flow in porous media, allowed us to characterize many of its features and enabled the development of specialized models of the phenomenon. There are many conditions in soil that allow instabilities to form and develop, including vertical flow from a fine textured layer into a coarse one, vertical flow into a compressed air phase, infiltration into water-repellent soil, two-phase flow involving two fluids of contrasting density and viscosity, infiltration into homogeneous soil at flux rates substantially less than the saturated hydraulic conductivity, and redistribution following infiltration. However, there is a challenge in characterizing the conditions of instability, modelling unstable flow features, unstable flow during redistribution and characterizing unstable flow in field soils.

2.2 Characterizing soil water repellence

When water does not bond to soil surfaces, the soil is deemed to be water repellent or hydrophobic. At the pore scale, water repellence alters the contact angle between the solid and liquid phases, which in turn reduces or eliminates the capillary forces stabilizing water in the soil. There is a challenge to develop robust models to account the soil repellence because of our limited understanding on the following aspects of soil repellence. It becomes difficult to predict when soil water repellence will occur, or disappear, and what impact these changed states might have on the regulating and provisioning of ecosystem services that are supported by soil functioning. Moreover, fuzziness also exits in the spatial extent and temporal duration of either potential (measured on oven-dry samples) or actual (measured on wet samples) soil water repellence, nor why potential repellence is not always present, and why sometimes it can be "washed out" and not reappear. Our ignorance is primarily because we do not understand the genesis of hydrophobicity at the pore-scale level. At the large scale, agronomists, ecologists, and resource economists need to integrate their knowledge for better understanding of water repellences into farm-scale and landscape modelling.

3. Incorporating the biological components of soil

3.1 Flow and transport in the soil-plant continuum

Our understanding of dynamic processes in the soil–plant continuum has greatly progressed in recent years due to the development of novel measurement technologies combined with increasing capabilities and progress in numerical modelling. However, we are still at the early stages of understanding how to describe different processes influencing flow and transport when plants are present *viz.*, modelling root water uptake, root-soil coupling and feedback mechanism and nutrient uptake by plant roots. Improving our understanding of soil–plant interactions will require well-designed experiments at the laboratory, plot, and field scales. Early stress recognition of plant stands has become possible due to the development of novel measurement techniques such as hyperspectral sensors operated at the plant stand, fluorescence and isotopic techniques. These new tools and techniques will help in assessing and understanding the flow and transport processes in soil-plant systems.

3.2 Physical and Ecological origins of soil microbiological diversity

The dynamics and spatial arrangement of water are particularly important for soil bacteria. The need to formulate quantitative links between hydrologic processes and microbial life in the soil is motivated both by fundamental ecological questions related to diversity and its maintenance as well as by practical environmental, agronomical, and engineering questions. For example, issues related to the introduction and stimulation of bacteria for remediation activities in the soil or the prediction of bacterially mediated nutrient cycles and gaseous fluxes at all scales. That is an interdisciplinary frontier area where soil physics can play an important role.

4. Soils and components of Ecosystem

4.1 Role of soil physics in ecosystem services

Despite its increasing adoption in science and policy, the ecosystems services approach cannot cope with the complexity and interconnectedness of natural systems because it is very difficult to isolate, quantify and thus value all the natural processes involved in the provision of a given service. It will also require an "ecological focus" as opposed to simply an "economic focus," and the development of knowledge that accounts for the interconnectivity and overall functioning of the ecosystem infrastructure (EI). This is not possible using the existing suite of economic and nonmarket valuations and scientific tools. Until a truly transdisciplinary engagement occurs, we will continue to treat soil like dirt and future generations will pay the price for a lack of investment in EI. Soil physicists have a great role to play for this issue in collaboration with other disciplines.

The challenges discussed here reflect inherent gaps between the complexity of the soil environment and its biogeochemical function, and the limited measurement and analytical tools at our disposal. Improving our predictive capabilities at relevant spatial and temporal scales is necessary to address some of the long-standing problems within agriculture and the soil environment.

Considering the new generation problems and associated challenges, Ahuja *et al*. (2006) identified the following transdisciplinary research areas for soil physicists.

(i) Climate change impacts on soil

Soil can serve as a source or sink of greenhouse gases *viz.*, CO_2, CH_4 and N_2O based on its management practices, which is the driving force for anthropogenic global warming and climate change. Therefore, soil physicists should work on this line in collaboration with scientists of other disciplines to develop management strategies for adaptation and mitigation of climate change.

(ii) Conservation agriculture practices

Conservation agriculture is a paradigm shift in agricultural practices which involves following three principles *viz.*, reduced tillage, residue retention and crop rotation and the new addition to this is controlled traffic. Tillage and subsequent reconsolidation due to wetting and drying can change bulk density and porosity, soil hydraulic properties, surface roughness and depression storage. Assessment and simulation of soil physical parameters and their consequent role on soil processes is great challenge before the soil physicists.

(iii) Soil carbon sequestration

Soil carbon sequestration is one of the win-win strategy for improving soil health and carbon sequestration. Unravelling the mechanism of soil carbon sequestration in different soil and crop management systems under varied agroclimatic system is a great challenge. Simulation of soil carbon pool dynamics and carbon sequestration under different management scenarios is a bigger challenge before the soil physicists.

(iv) Environmental pollution

Soil and water pollution due to different types of industrial effluents and indiscriminate use of inputs in agriculture, dynamics of the pollutants in the soil-plant system, their simulation and management is a great challenge before the soil physicists.

(v) Use of plastics

Indiscriminate use of plastics and consequent impact on soil health and groundwater recharge should be assessed and managed by the soil physicists in association with the scientists of other disciplines.

(vi) Land degradation

Land degradation and deterioration of soil health is the major threat to sustainable agriculture. It is unfortunate but true that almost 30% of the World's soils has been degraded due to unstainable management practices, with a degradation trend for arable land continuously arising from highly intensive agricultural practices and global change (Nascimento *et al.*, 2021). Importance of sustainable land management was acknowledged in the IPCC Special Report on Climate and Land (IPCC, 2019), highlighting the interactions and feedbacks between changing climate, land degradation, sustainable land management and food security. This is an important aspect, wherein soil physicists can make significant contributions in collaboration with soil conservationists and other sister disciplines.

Recent advances in soil physics research

In the face of the challenges in soil physics research as discussed above the soil physics research has made significant developments on basic understanding of physical, mechanical and hydrological properties and process of soil, its impact on environment, agricultural production and sustainable use of natural resources especially through the use of sensors, soil databases and modelling techniques employed into soil-plant-atmosphere continuum and environmental modelling.

Some of these recent advances in soil physics research is given below.

(i) Advancement in measurement techniques

Advancements in measurement techniques play a crucial role in advancing the field of soil physics. Accurate and precise measurements of various soil properties are essential for understanding soil behavior and optimizing land management practices. Technological and methodological advancement is a key in improving our understanding of soil physical processes and a prerequisite for successful testing of hypotheses. Hypothesis driven soil physical principles need access to high-quality data with the best possible temporal and spatial resolution to testify the hypotheses.

Here are some recent advances in measurement techniques in the context of soil physics:

a. *Advanced Sensors for different soil parameters*: Development of advanced sensors and sensing systems with improved accuracy and precision to measure different soil parameters such as soil moisture (TDR, FDR, capacitance), temperature, electrical conductivity, and salinity in near real time or real time basis. Emerging technologies include multi-sensor systems that would provide a more comprehensive view of soil conditions.

b. *High-Resolution Soil mapping***:** High-resolution soil sampling techniques, such as geostatistical sampling and digital soil mapping, enable the collection of soil data at finer spatial scales. This allows for a more detailed characterization of soil variability across landscapes.

c. *Proximal Soil Sensing*: Proximal soil sensing involves collecting data from close to the soil surface using various sensing technologies. Near-infrared spectroscopy, electromagnetic induction, and gamma-ray spectrometry are examples of proximal sensing methods that provide rapid and non-destructive measurements of soil properties.

d. *X-ray Computed Tomography (CT)***:** X-ray CT imaging has become more sophisticated, allowing researchers to visualize and analyze soil structure in three dimensions. This technique provides detailed insights into soil pore structure, aggregate distribution, and root architecture without disturbing the soil. At the finer resolution level, tomographic techniques that operate at the soil column scale, such as X-ray CT tomography (Carminati *et al*., 2010) and microtomography (Aravena *et al*., 2011), neutron tomography (Oswald *et al*., 2008; Carminati *et al*., 2010, Moradi *et al*., 2009), and nuclear magnetic resonance imaging (Pohlmeier *et al*., 2013), are very useful. Tiana *et al*. (2008) observed that in agriculture the X-ray CT can be used to investigate the hydro-physical characteristics of the soil, in a functional and temporal manner. These techniques could measure the impact of roots on rhizosphere properties (compaction and wettability) and demonstrate the effect of these properties on root water uptake.

e. Magnetic Resonance Imaging (MRI): MRI techniques have advanced for studying soil water dynamics and moisture distribution in the vadose zone. MRI allows non-invasive monitoring of water movement within the soil profile over time, providing valuable information for understanding soil-plant-water interactions.

f. *Laser-Induced Breakdown Spectroscopy (LIBS)*: LIBS is an analytical technique that has been explored for soil analysis. It enables rapid elemental analysis of soil samples, offering a quick and non-destructive method for assessing soil composition.

g. *Automated Soil Sampling and Analysis Systems:* Automated soil sampling systems, coupled with on-site analysis technologies, have streamlined the process of collecting and analyzing soil samples. These systems provide real-time data for soil nutrient content, pH, and other essential properties.

h. *Isotopic Tracers for Water Dynamics*: Stable isotopes, such as deuterium and oxygen-18, are increasingly used as tracers to study water movement in soil-plant systems. Isotopic techniques help researchers trace the sources and pathways of water in the soil and assess plant water uptake dynamics.

i. *Advancements in Spectroscopy Techniques:* Spectroscopy techniques, including mid-infrared and visible-near-infrared spectroscopy, have seen improvements in terms of accuracy and range. These techniques allow for rapid and non-destructive analysis of soil properties, including organic matter content and mineral composition. Researchers are able to determine soil properties, even for soils under vegetation, with the use of hyper spectral sensors and MIR spectroscopy-based soil reflectance analysis. The stratification of nutrients most commonly reported in fields under agriculture could be more easily identified using rapid measurement of soil properties using MIR and NIR spectroscopy techniques in combination.

j. *Microwave remote sensing for soil moisture estimation*: Measurements of electromagnetic energy, that has either been reflected or emitted from the soil surface, through microwave remote sensing provides an all-weather capability for measuring the spatial distribution of soil moisture content for regions with low to moderate levels of vegetation cover, but is limited to the top few centimetres of soil and to a revisit interval of once in every few days. Recently launched NASA's Soil Moisture Active Passive (SMAP) mission is designed to monitor from space soil surface moisture content around the world in an effort to improve forecasts of hazards such as droughts and floods. This technique has great potential for estimation of soil moisture in areas under agriculture in association with profile moisture dynamics models for prediction of water balance of the system and improvement of water productivity.

These measurement techniques contribute to a more comprehensive understanding of soil physics, enabling researchers to assess soil properties with higher precision and efficiency. The integration of these advanced measurement tools supports sustainable land management practices and enhances our ability to address environmental challenges related to soil health and resource management.

(ii) Modelling and simulation

Recent advances in soil physics have significantly influenced the field of modelling and simulation. These computational approaches help researchers and practitioners understand complex soil processes, predict soil behaviour under different conditions, and optimize land management practices. Integration of soil-water-plant-atmosphere models has become more sophisticated. These models simulate the interactions between soil, water, plants, and the atmosphere considering factors such as water movement, nutrient cycling, and energy balance. Improved coupling between these components enhances the accuracy of predictions in various environmental conditions. Advances in high-performance computing have enabled the development of more complex and detailed soil physics models. These models can simulate processes at finer spatial and temporal resolutions, providing a better understanding of soil dynamics (Chaudhary *et al.*, 2018). Advances in uncertainty quantification methods help modelers assess the reliability and robustness of their predictions. Monte Carlo simulations and probabilistic modelling approaches are used to account for uncertainties in input parameters and model structures.

Due to complex nature of the soil system, very little is known about how structure changes with time which affects the soil hydrological properties. In the last 25 years soil physicists have taken on the challenge of addressing real problems and moved from laboratory scale stands to field and landscape scales by modelling various physical properties and processes. Simpler equations have been modified and integrated to complex integrated models using fast computing by modern computers. Scope of soil physics has gradually expanded towards interdisciplinary boundaries because of central role of water in agriculture systems. Soil physics research in interfacial areas include modelling the linkage of transpiration with photosynthesis, energy balance of crop canopies (Van Bavel and Lascano, 1987) crop water uptake (Campbell, 1991), root growth modelling (Benjamin *et al.*, 1996) and nutrient uptake by roots. Simulation models are used to further understand flow and transport behaviour and to perform scenario analyses in soils. Crop growth and yield as determined by weather and soil type can be understood better by soil water and nutrient dynamics along with the development of the crop. So, soil physical processes along with temporal and spatial estimation through modelling have become helpful in extrapolating the limited information from one location to the other. All the soil physical processes such as evaporation, infiltration, and runoff etc which are part of the water balance has been simulated using suitable modelling techniques. Most of the crop simulation models have sub modules for water balance and solute flow which are governed by the demand and supply of water by the crops according to the environmental condition. Some of the examples are EPIC (Erosion Productivity Impact Calculator) model (Williams *et al.*, 1984) to estimate bulk density after tillage, RZWQ (Root Zone Water Quality) model (Ahuja *et al.*, 2000) to predict soil reconsolidation after tillage, estimation of è(h) from soil texture (Rawls *et al.*, 1982), estimates of pore size distribution as affected by tillage (Ahuja *et al.*, 1998; Or *et al.*, 2000), a model linking soil hydraulic properties to soil morphology structure and aggregation (Lilly and Lin, 2004) and simple model of soil shrinkage curve by Peng and Horn (2005). Few other important models developed are, SALUS (System Approach to Land Use Sustainability) designed to model continuous crop, soil, water and nutrient conditions under different management strategies (Basso *et al*., 2006), HYDRUS, which models environment for the analysis of water flow and solute transport in variably saturated porous media, simulating the two- and three-dimensional movement of water, heat, and multiple solutes and numerically solves the Richards equation for saturated-unsaturated water flow and convection-dispersion type equations for heat and solute transport (Simunek *et al*., 2012), SoWaM (Soil Water Management) model for simulating 1-Dimensional flow in porous media (Wesseling *et al*., 2009) and Soil Plant Air Water (SPAW) model (Saxton and Willey, 2006) relating field hydrology and soil water to rainfall, temperature, evaporation and crop growth. Three-dimensional modelling of soil properties and processes has become more common. Advanced visualization techniques, including virtual reality and augmented reality, provide a more intuitive understanding of soil structure, water movement, and root architecture. Soil physics models are increasingly used to assess the impacts of climate change on soil properties and processes. These models help predict changes in temperature, precipitation patterns, and extreme weather events, providing insights into potential shifts in soil behavior.

(iii) Use of AI/ ml technologies in Soil Physics Research

Artificial intelligence (AI) which is a game-changer in other sectors, can be a potential tool and technology in agriculture also (Sarkar *et al*., 2022). A smarter, agile and environmentally sensible parameters can be driven by big data, Internet of Things (IoT), artificial intelligence (AI) and machine learning. AI based techniques can be used in several aspect of natural resource management, especially in soil science. Machine learning and AI techniques are increasingly applied to soil physics modelling. These methods can identify complex patterns and relationships within large datasets, helping to develop more accurate predictive models for soil properties and processes. Efforts to develop a global soil information system involve integrating large-scale soil databases with modelling approaches. This allows for the creation of global soil maps and facilitates the assessment of soil related issues and challenges on a broader scale. Soil risk characterization decision support system (SRC-DSS) is an AI based decision support system which uses fuzzy logic to characterize soil as well as to identify contaminated soils which possess accidental risk. The fuzzy logic also has an advantage to remove imprecision or uncertainty in soil management data, only a few parameters are needed to quantify the soil (López *et al*., 2008). The parameter which takes considerable time to estimate can be easily measured by artificial neural networks (ANN). Soil hydraulic conductivity which is difficult to measure can be predicted easily by measurable soil parameters like soil texture data (sand and clay contents), soil water retention curve e.g. van Genuchten retention model parameters, bulk density, and effective porosity (Ghanbarian-Alavijeh *et al*., 2010). Soil field capacity moisture content can be successfully predicted by ANN (Bhattacharya *et al*., 2018). AI based machine learning approaches like support vector machine (SVM) can predict mean weight diameter of soil (Bhattacharya *et al*., 2020). It was seen that the random forest model has become more efficient than any other machine learning approaches in classification of soil based on their quality (Rao, 2019). Not only physical parameter but also biological parameter like soil enzyme activity can be predicted by using artificial intelligence tools and techniques, which is proved to be better predictor than Multiple Linear Regression (MLR) and also found that when Digital Terrain Model (DTM) is attached with ANN, it gives better mapping of soil enzyme activity (Tajik *et al*., 2011). Moreover, use of concepts based on real field situation when coupled with the AI based estimations; the pure black box nature of modelling is translated to a grey box model ensuring its wider applicability.

Conclusions

Sustaining the agri-food system under changing climate, land degradation, soil health deterioration, decline in factor productivity and dwindling quality and quantity of water resources is a Global problem. Soil physicists can play a significant role to address these problems and restore the ecosystem services of the soil. In the recent days, new challenges have emerged *viz.*, climate change, land degradation, soil fertility decline, multi-nutrient deficiency, environmental pollution, greenhouse gases emissions etc. To meet these challenges there is need for reorientation in soil physics research priorities. Recent advances in the use of measurement tools, improved understanding of soil physical processes and modelling and use of modern tools and application of AI and ML techniques would ensure attaining better soil health for sustainable agri-food system with minimal environmental pollution.

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AI and Smart Agriculture

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ABSTRACT

Agriculture as an industry remains a core mission to transform our world to zero hunger with food and nutritional security promoting sustainable agriculture, responsible consumption and production, under changing climate, food, and demography for an indeterminate time-horizon. Recent developments in the technologies for Smart Agriculture in the field of sensors, Internet of Things (IoTs), remote sensing at different platforms, drone technology, geospatial sciences, big data analytics, robotics, Spatial Decision Support Systems (SDSS), Variable Rate Technology (VRT), Digital Soil Mapping (DSM), Information and Communication Technologies (ICTs) have special advantage in terms of generating state-of-the art informatics - capturing the variability, vulnerability and dynamism of agricultural system for spatio-temporal monitoring crop, soil and micro-environment and are proving to be the key to breaking the bottlenecks for enhanced resource use efficient, environmentally safe and optimized agri-production system. This paper highlights some of new edge developments on AI and Smart Agriculture which has been envisaged for future farm.

Introduction

Over the previous several decades, farming practices across the globe have undergone a varied range of technical revolutions; is marching towards industrialisation and is becoming technology-driven. In recent years, the agricultural sector has witnessed a significant transformation driven by advancements in technology, particularly Artificial Intelligence (AI) (da Silveira *et al.,* 2021). Smart agriculture, also known as precision agriculture, leverages AI and various other technologies to revolutionize traditional farming practices. AI and smart agriculture together represent a transformative intersection of technology and farming practices aimed at enhancing efficiency, sustainability, and productivity in the agricultural sector through the use of intelligent agricultural technologies, making them more predictable and efficient (Rose and Chilvers, 2018). Farmers in turn are getting benefitted by having an increased control over crop production. These technological advancements have not only aided the crop production but have also impacted the lives of farmers in a positive and a revolutionary way. This, combined with rising consumer demand for farm products, has aided the spread of smart farming technology worldwide (Latino *et al.,* 2021, Letizia *et al.,* 2019).

This digitisation and upward mobility have led us to Precision agriculture that entails the precise management of agricultural inputs and practices based on real-time data and analytics (A. T. and Toscano, 2020). It involves the use of AI, IoT (Internet of things) sensors, drones, and satellite imagery to collect and analyse data on soil conditions, weather patterns, crop health *etc*. It not only enhances the decision-making processes related to irrigation, fertilization, and pest control but also leads leads to increased yields and resource efficiency (Kong *et al.,* 2019).

Agriculture as Industry 5.0

A revolution and concept going way beyond the traditional manufacturing with emphasis on integration of humans and machines to collaborate more effectively is referred to as Industry 5.0 (Fraga *et al.,* 2021). It marks a noticeable change from Industry 4.0 that focused majorly on automation, data exchange and adoption of smart technology in the field of agriculture (Skobelev & Borovik, 2017). The additions in Industry 5.0 enables the farmers to leverage data analytics, sensors, and IoT devices to make more informed decisions about planting, irrigation, fertilization, and pest control. Instead of replacing humans with machines, Industry 5.0 in agriculture emphasizes collaboration between the farmers and technology. The labor-intensive tasks are performed by the advanced instruments while the decision making and control stands in the hands of the stakeholders (Rane, 2023; Adel, 2022). This technology goes beyond the hard coding and enables the customizations and personalization based on the user specific needs and environmental conditions. Here, integration with blockchain technology is used to create transparent and traceable supply chains, ensuring food safety and quality while reducing waste and inefficiencies (Akundi *et al.,* 2024). Going beyond the technology, it also works forward towards enhancing the skills and training of the farmers to keep them well updated of the changing technologies and to help them stay competitive in a rapidly evolving agricultural landscape (Mourtzis *et al.,* 2022). The technology also aims to promote the sustainable and resilient agricultural practices. By combining traditional wisdom with cutting-edge technology, farmers can adopt regenerative farming methods that enhance soil health, biodiversity, and ecosystem resilience while mitigating the effects of climate change. It holds immense potential to reshape agricultural landscape, helping us to march into a future where human creativity seamlessly merges with cutting-edge technology, unlocking the full capabilities of Industry 5.0 (Figure 1) and setting up grounds for Society 5.0 (Aggarwal *et al.,* 2024, Paschek *et al.,* 2024).

Cyber Agrophysical System (CAPS)

Cyber Agro-Physical System (CAPS) is Cyber Physical Systems in Agriculture in which computation/information processing and physical processes are tightly integrated and non-separable from the behavioural point of view; where functionality and salient system characteristics are emerging through the interaction of physical and computational objects; and computers, networks, devices and their environments in which they are embedded have interacting physical properties, consume resources, and contribute to the overall system behaviour. Such agricultural systems and

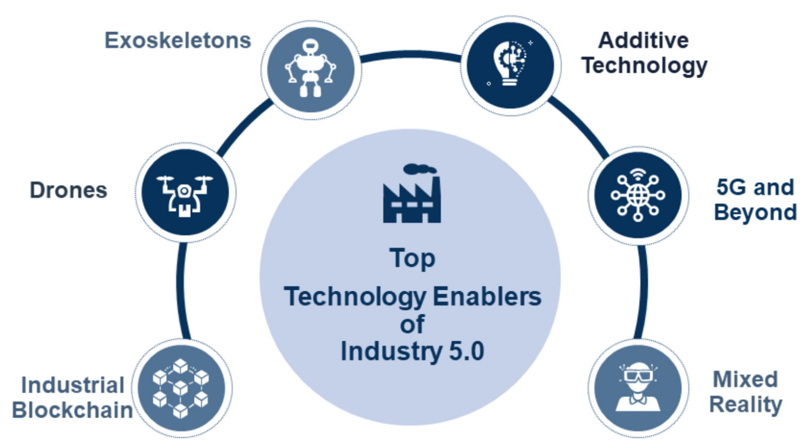

Figure 1. Technology enablers of Industry 5.0 (Source: https://www.frost.com/frost-perspectives/industry-5-0-bringing-empowered-humans-back-to-the-shop-floor/)

approaches constitute the paradigm of intelligent agriculture, based on quality, efficiency and sustainability requirements. The implementation of such a system could be made by degrees, stepwise increasingly both the production diversity and the automation level, thus ensuring a lean transition from a monoculture specialized agricultural enterprise towards a flexible, diversified, adaptive improved version and making agriculture as Industry 4.0 /5.0 with good agricultural practice (GAP) and new way of connectivity of digital and physical world.

Artificial Intelligence (AI)

Artificial Intelligence (AI) is characterized as machine intelligence designed to emulate human-like functioning. It serves as a cognitive engine, facilitating analysis and decision-making based on data acquired from various sources. AI processes this acquired information to derive meaningful insights.

Artificial Intelligence in IoT (Internet of things) involves embedding AI technologies, such as machine learning, deep learning, and natural language processing, into IoT devices, sensors, and platforms to enable smart decision-making, learning, and autonomous actions (Figure 2 and 3).

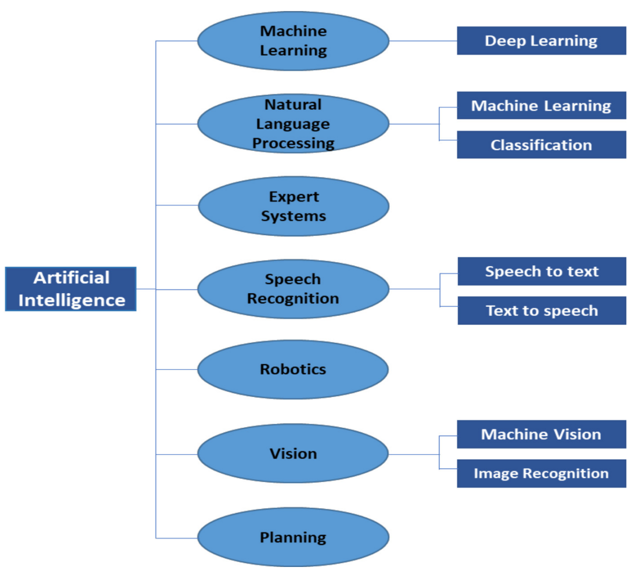

Figure 2. Constituents of Artificial Intelligence

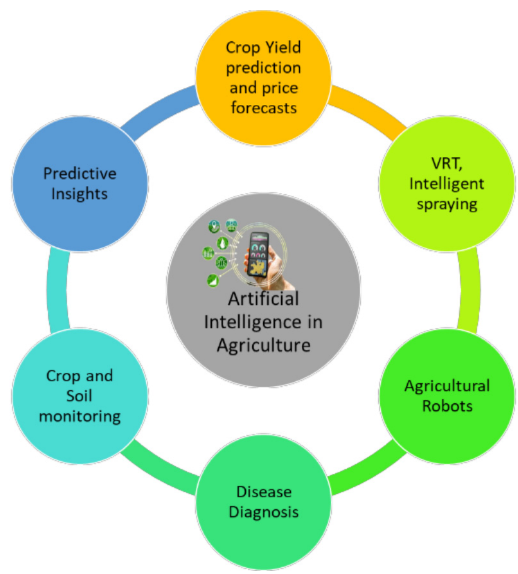

Figure 3. Artificial Intelligence in Smart Agriculture

AI aims to enhance the intelligence and efficiency of IoT deployments by leveraging AI algorithms and techniques, facilitating predictive maintenance, and identifying patterns or anomalies. Machine learning is essentially the scientific approach enabling machines to interpret, process, and analyse data for the purpose of addressing real-world issues. It can be understood as a subset of Artificial Intelligence (AI) that imparts machines with the capacity to autonomously learn and enhance their performance through experience, without explicit programming.

In essence, machine learning involves empowering machines to think and solve problems. This discipline relies on vast amounts of both structured and unstructured data, ensuring that machine learning models deliver accurate results or predictions based on the acquired knowledge. Machine learning contributes to smart automation and behavioural analytics, allowing IoT devices to adapt and optimize processes based on user behaviour. The convergence of AI and IoT holds tremendous potential, ushering in a new era of intelligent, adaptive, and efficient systems.

Smart Agriculture

Smart Agriculture being conducted on a large scale using the IoT, artificial intelligence (AI), and agricultural data analysis utilises technologies such as climate-smart agriculture (CSA), climate-smart forestry (CSF), climate-smart rangeland management, and climate-smart livestock production. is in developed nations according to (Goel *et al.*,, 2021). Smart agriculture (SA), the integration of traditional production and the Internet of Things, is an evolution of precision farming (PF) (Mazzetto *et al.*,, 2020) that has boosted agriculture production due to the high potential to assist farmers (Sharma *et al.*,, 2022).

Smart agriculture brings numerous benefits to agricultural production through weather monitoring, groundwater detection, and temperature control. IoT-based smart agriculture's common practices include smart farming for sustainable agriculture and smart crop rotations that mitigate issues and challenges related to weeds, plant disease, insects, and other pests according to (Zikria *et al.,* 2021). The use of smart agriculture on farms is gradually spreading and provides a scope for the promotion of increased production techniques. Smart farm technology implemented and adopted under NePPA (Network Program on Precision Agriculture) at Indian Agricultural Research Institute (IARI), ICAR is shown as under in Figure 4.

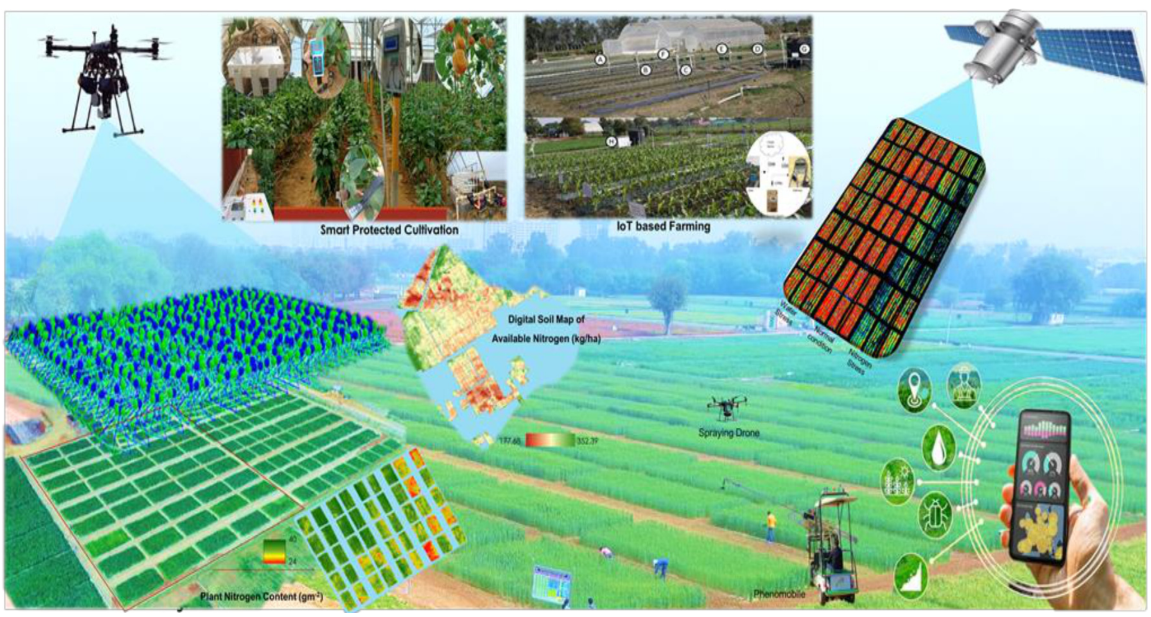

Figure 4. Smart Farming (Source: ICAR-NePPA)

Techniques for implementing AI and Smart Agriculture

Machine Learning approaches

Machine learning approaches (Table 1) are categorized into Supervised Learning, Semi-supervised learning, Unsupervised Learning and Reinforcement Learning. A supervised learning algorithm gains knowledge from labelled training data, enabling it to make predictions for new, unseen data. For instance, supervised learning can be employed to predict crop yield or disease and pest detection based on training data. In this scenario, the input variables may include factors such as the geographic location, weather patterns, soil quality etc. locality and size of a house. Semi-

Table 1. Some of machine learning models commonly used in agriculture (modified from Sahoo *et al.,* 2023b)

S.No.	Algorithm	Features
1.	Kernel ridge regression (KRR)	Kernel is introduced to RR. Uses squared error loss. Faster for medium-sized datasets. Matrix inversion
2.	Least squares linear regression (LSLR)	Model the relationship between a dependent variable and one or more independent variables. Does not consider the complexity of data.
3.	Neural network (NN)	Approach that uses a standard back-propagation algorithm applied to a set of input, hidden, and output layers. Predicts the results for unknown datasets. Requires labelled data for the training process. The training of the network takes time.
4.	Support vector regression (SVR)	Works on the concept of maximizing the margins. Generates a decision boundary with maximum separation. Proves helpful when multiple heterogeneous classes are available.
5.	Extreme learning machine (ELM)	Learning algorithm for single-layered feed-forward neural network. Fast learning. Computationally scalable. Independent from the tuning process. Evaluation speed is low.
6.	Bagging trees (BaTs)	General-purpose procedure for reducing the variance of a statistical learning method. makes predictions on the tree's out-of-bag observations. Multiple trees can be trained simultaneously. All the trees trained on different bootstrap samples are correlated.
7.	Boosting trees (BoTs)	Transforms weak decision trees (called weak learners) into strong learners. Tends to overfit. Better than random predictions. Good at handling tabular data with numerical features. Able to capture nonlinear interactions between the features and the target. Not designed to work with very sparse features.
8.	Random Forest	An ensemble approach uses decision trees. Creates multiple decision trees on different data samples and then predict the data from each subset. Finally, the forest (group of random trees) is averaged.
9.	Gaussian Process regression (GPR)	Probabilistic (Bayesian) approach, an additional quantitative measurement of prediction accuracy in terms of uncertainty estimates, use of kernels or covariance functions to reduce the processing time.
10.	Partial least square regression (PLSR)	Combines the benefits of principal component analysis and multivariate linear regression by reducing data dimensionality, transformation, and regression

supervised learning is a machine learning paradigm that lies between supervised learning and unsupervised learning. In this approach, the model is trained on a dataset that contains both labelled and unlabelled examples. In semi-supervised learning, a portion of the training data is labelled, and the rest is unlabelled. The model is trained on both the labelled and unlabelled data to learn patterns and relationships. This can be especially useful when obtaining labelled data is expensive or time-consuming, as it allows the model to leverage the available labelled examples along with the potentially larger pool of unlabelled data. Semi-supervised learning methods aim to improve the performance of machine learning models by combining the benefits of supervised and unsupervised learning, making it a practical choice in scenarios where acquiring labelled data is a limiting factor. Unsupervised learning entails training with unlabelled data, enabling the model to operate without explicit guidance. It can be applied to predict "Human Behaviour," where a learner equipped with advanced visual and speech recognition capabilities observes numerous television shows to learn about human behaviour. For instance, the learner could develop a model capable of detecting when people are smiling, correlating facial patterns with spoken words like "what are you smiling about. Reinforcement Learning is a form of machine learning that enables software agents and machines to autonomously ascertain optimal behaviour to enhance system performance. This approach is prominently employed in sophisticated machine learning domains, including applications like Autonomous Machinery Control (Agriculture robot), Irrigation Optimization etc.

Deep Learning / Artificial Neural Networks

Deep Learning is the process of implementing neural networks on the high dimensional data to give insights and provide solutions. The use of Deep Learning in different fields of agriculture, including smart farming is seed analysis, water management, soil analysis, weed and pest detection, stress detection, plant disease detection, and crop yield detection.

Artificial Neural Networks consist of artificial neurons referred to as units, organized in layers that collectively form the entire neural network within a system (Figure 5). The number of units in a layer can vary significantly, ranging from a dozen to millions, depending on the complexity required for the neural network to discern hidden patterns in the dataset. Typically, an Artificial Neural Network includes an input layer, an output layer, and hidden layers. The input layer receives external data that the neural network aims to analyse or learn from. Subsequently, this data traverses one or multiple hidden layers, where it undergoes transformations to become valuable input for the output layer. Ultimately, the output layer generates a response, presenting the output of the Artificial Neural Network in response to the provided input data.

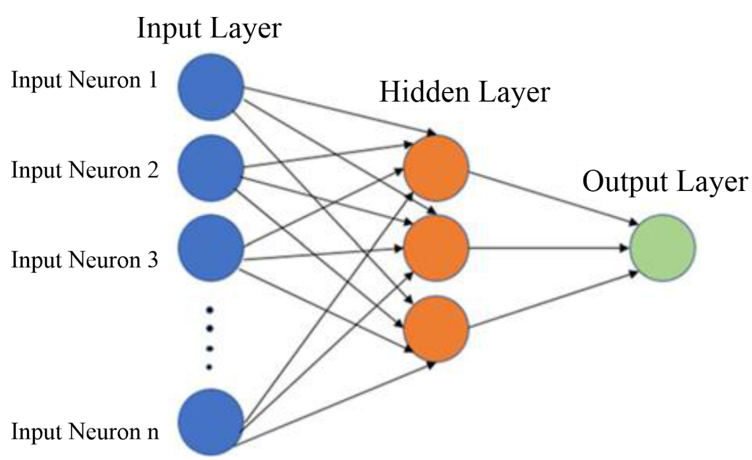

Figure 5. Basic architecture of artificial neural network (ANN) (Sahoo *et al.,* 2023b)

In most neural networks, units are interconnected between layers, and each connection possesses weights that dictate the impact of one unit on another. As data moves from one unit to another, the neural network progressively learns more about the data, culminating in an output from the output layer.

The structures and functions of human neurons form the foundation for artificial neural networks, commonly referred to as neural networks or neural nets. The initial layer in an artificial neural network is known as the input layer, responsible for receiving input from external sources and transmitting it to the subsequent layer, known as the hidden layer. Within the hidden layer, each neuron receives input from neurons in the preceding layer, computes the weighted sum, and transmits the result to the neurons in the subsequent layer. These connections involve weighted means, where

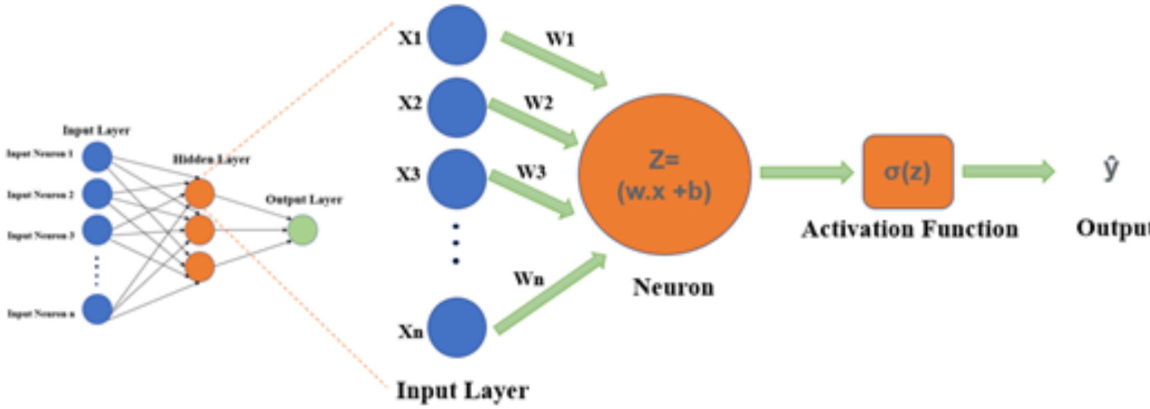

Figure 6: Basic architecture of artificial neural network (ANN) (Sahoo *et al.,* 2023b)

the impacts of inputs from the preceding layer are fine-tuned by assigning varying weights to each input. These weights are adjusted during the training process to optimize model performance (Figure 6).

The major advantage of neural networks is their ability to predict and anticipate via parallel thinking. Artificial Neural Network can be taught instead of being extensively programmed. Relationship between AI, ML and Deep Learning/ Neural Network is depicted in Figure 7.

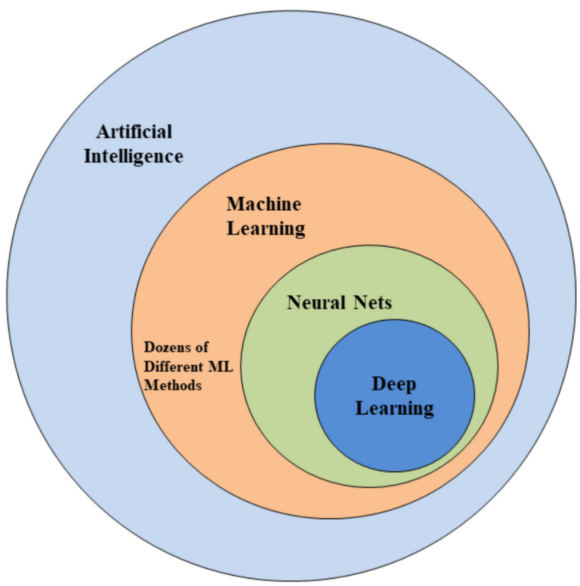

Figure 7. Relationship between AI, ML and Deep Learning/ANN

Hybrid ML approach using Gaussian Process Regression (GPR)

Gaussian process regression (GPR) provides a probabilistic (Bayesian) approach for learning generic regression problems with kernels (Verrelst *et al.,* 2013). On compared with other ML models, the GPR shows two major advantages of generating additional quantitative measurement of standard deviation and coefficient of variation (CV) along with prediction estimates and second is the use of kernels of co-variance functions to reduce the time taken during training the model. The Figure 8

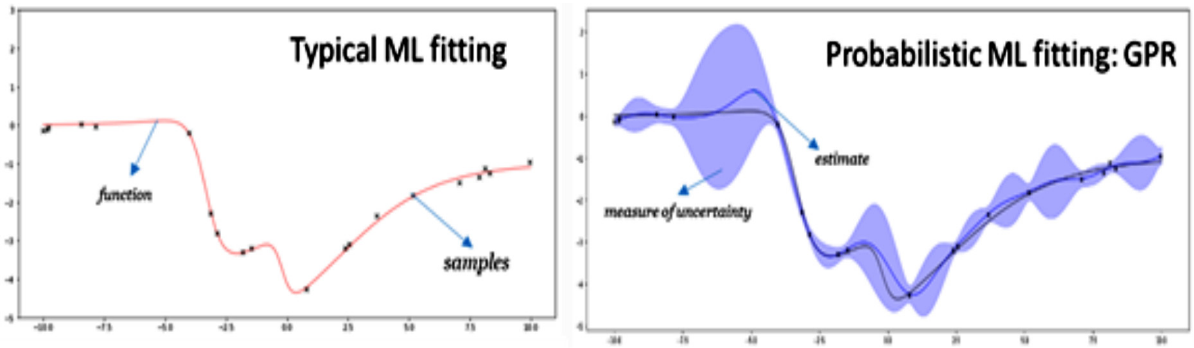

Figure 8. Regression with Gaussian Processes (Source: https://jessicastringham.net/2018/05/18/Gaussian-Processes/)

clearly gives a differentiation of GPR fitting with a typical ML fitting. The uncertainty can be noticed at regions where there are large gaps of missing data points. The squared exponential is the widely used kernel function for retrieving crop traits from multispectral and hyperspectral datasets. The best prediction performance for GPR models can be achieved by integrating with radiative transfer models. This hybrid modelling approach with the aid of dimensionality reduction and active learning techniques demonstrated accurate retrieval of multiple cropland traits using satellite and UAV borne datasets (Sahoo *et al.,* 2023a).

The hybrid model combines the capabilities of RT modelling with the help of non-parametric regression models. The simulated spectral data front the RT modelling is used for training the GPR model. Several active learning methods were also used for reducing the training size of model, making it lighter to integrate with online platforms such as Google Earth Engine to generate accurate maps of multiple crop traits of larger areas (Sahoo *et al.,* 2023a).

Generative AI and Agriculture

Generative AI is a ground-breaking advancement that refers to the algorithms and models which are capable of generating new, original content based on patterns and examples learned from training data (Olaniyi *et al.,* 2022; Ray, 2024). Generative models, such as Generative Adversarial Networks (GANs) and Variational Autoencoders (VAEs), utilize neural networks to learn and mimic the underlying structure of data, enabling the generation of realistic outputs (Lu *et al.,* 2022) (Figure 9 and 10).

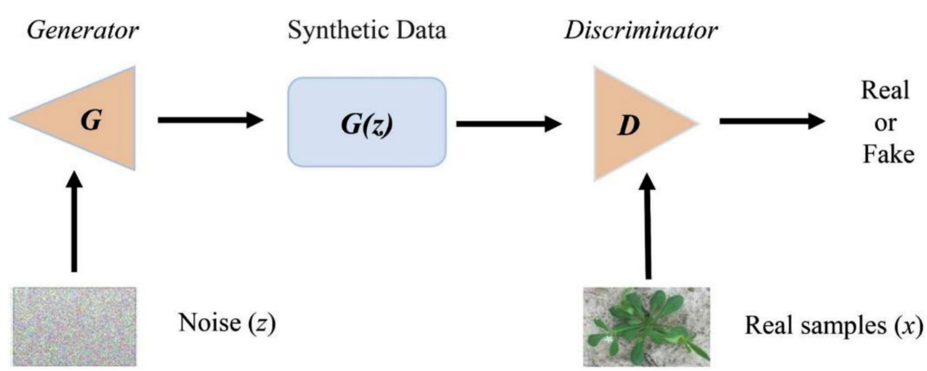

Figure 9. The framework of a vanilla generative adversarial network (GAN) that consists of two main models, i.e., the generator (G) and the discriminator (D) (Source: Lu *et al.,* 2022)

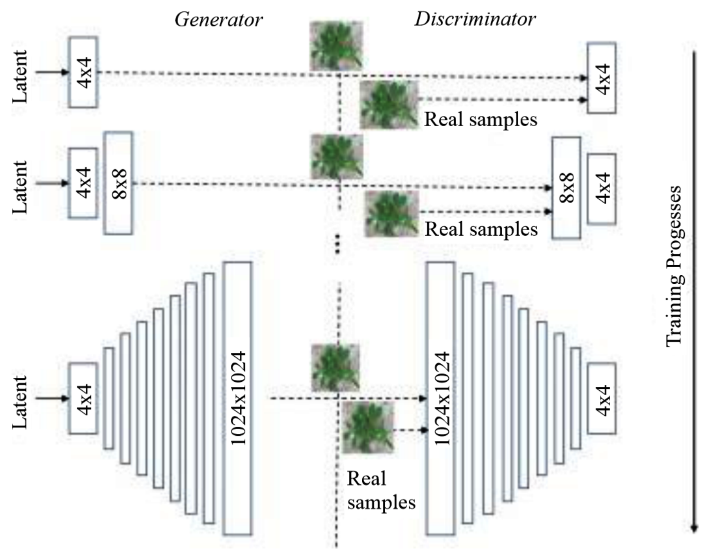

Figure 10. The architecture of progressively growing GAN (Source: Lu *et al.,* 2022)

Generative AL holds immense potential in the context of achieving the objectives of smart agriculture. It can aid in crop simulation modelling by simulating the crop growth patterns considering the factors such as soil type, weather conditions, and agricultural practices. These simulations further aid in prediction of crop yields, optimising the planning schedules followed by designing of the production strategies (Akkem *et al.,* 2024). Generative AI models can be trained on images of diseased crops that can generate synthetic images representing disease symptoms and stages. Similarly, it can be used to generate synthetic climate data based on historical weather patterns and climate change patterns for climate and environmental modelling.

For planning and execution of precision agriculture, synthetic field maps depicting the properties of soil, topography and vegetation indices at high resolutions can be generated using generative AI. The synthetic maps may be used to plan precision agriculture interventions such as variable-rate fertilizer application and irrigation scheduling, optimizing resource use and maximizing yields. For setting up autonomous Robotic farming, this technology can be used to train virtual environments for simulating robotic farming tasks such as harvesting, weeding, planting etc (Arora *et al.,* 2020). The intense training datasets that are generated contribute to the increased adaptability and performance of these autonomous robots.

AI can be integrated with metaverse to enhance the agricultural education and facilitate virtual collaboration among stakeholders (Figure 11). Virtual training scenarios can simulate real-world field conditions and challenges, allowing farmers to gain practical skills. AI algorithms can power virtual marketplaces within the agricultural metaverse, where farmers can buy and sell agricultural products, equipment, and services. AI-driven collaborative platforms in the agricultural metaverse can facilitate virtual collaboration among researchers, agronomists, and agricultural experts from around the world.

Digital Twin

The transformation of agriculture sector is moving to accomplish the demands of efficient and sustainable production. In this attempt, a digital twin is another step forward to modern smart farming. It is a digital replica of a real-world entity that is kept updated with constant inflow of and

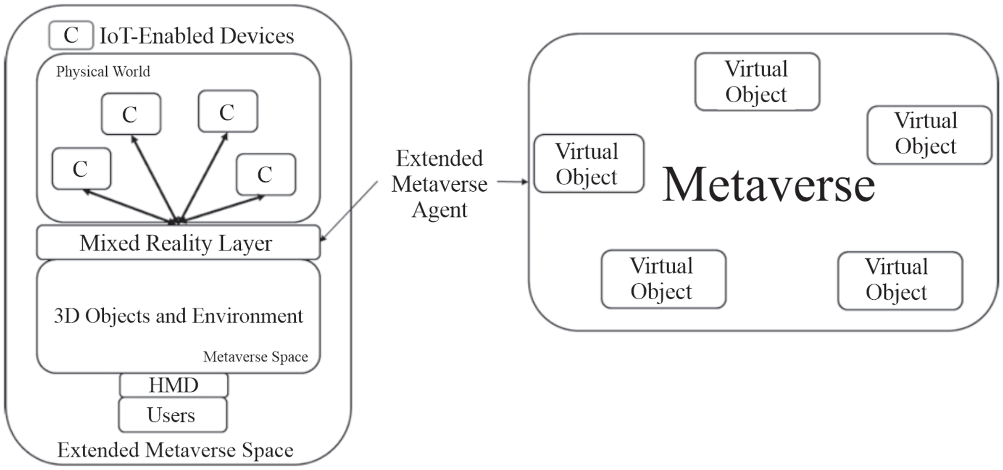

Figure 11. The framework of the extended metaverse agent, integrating the metaverse of virtual objects with XR/IoT environments (Source: Rekimoto and Nagao (1995))

simulates not just the the physical and biological state but also the behaviour of the real-world entity based on input data (Neethirajan and Kemp, 2021) (Figure 12). It helps in predicting, optimizing, and improving decision making. Integration of Digital Twin (DT) and Generative Artificial Intelligence (AI) has emerged as promising technology in agricultural sector (Du *et al.,* 2023). By leveraging immersive virtual environments and AI-driven technologies, stakeholders in the agricultural sector may enhance productivity, sustainability, and resilience in farming practices while fostering global connectivity and knowledge exchange (Nie *et al.,* 2022).

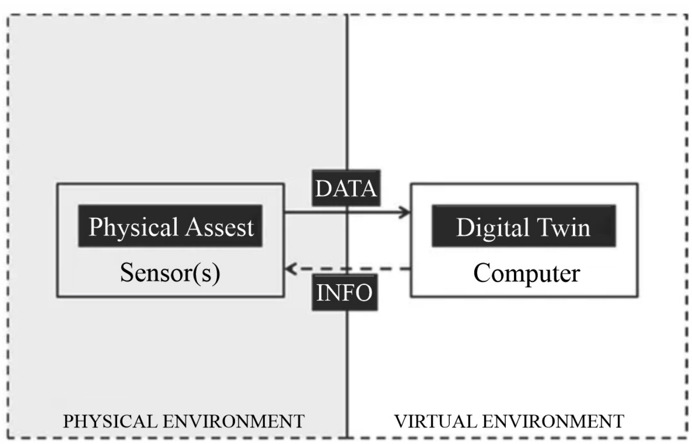

Figure 12. The relationship between digital twin and the physical asset (Source: Neethirajan and Kemp, 2021)

Applications of AI in Agriculture

Yield prediction

Several machine learning models were used to support crop yield estimation using remote sensing data. As per a Systematic Literature Review (SLR) conducted by (van Klompenburg *et al.,* 2020), the most applied ML algorithm is Artificial Neural Networks and the deep learnimng model is Convolutional Neural Networks (CNN). The outperformance of other ML models like Bayesian regularization BP (back propagation) neural network, Support Vector Regression (SVR), Extreme Learning Regression (ELR), Random Forest Regression (RFR), and Partial Least Squares Regression (PLSR) were also observed for estimating the crop yield using UAV and satellite remote sensing data (Kumar *et al.,* 2023; Maimaitijiang *et al.,* 2021; Xu *et al.,* 2021). Vegetation indices like Red edge, canopy chlorophyll content index, red edge chlorophyll index, chlorophyll absorption ratio index, green normalized difference vegetation index, green spectral band, and chlorophyll vegetation index were among the most suitable variables in predicting crop yield using ML models. Timely prediction of multi-stage crop yield with ML models using a limited number of training data is vital in crop management.

Pest and diseases detection

Early detection of crop disease is vital to prevent possible losses on crop yield. The accurate estimation of crop disease requires modern data analysis techniques such as machine learning and deep learning. The Figure 13 shows the important deep learning and machine learning techniques applied to UAV data for identifying crop diseases (Shahi *et al.,* 2023). MLR models successfully identify Maize Dwarf Mosaic Virus and wheat Powdery Mildew Disease from Hyperspectral Measurements (Khan *et al.,* 2021; Luo *et al.,* 2021), Kiwifruit Decline Syndrome from UAV multispectral data (Savian *et al.,* 2020), etc. These studies facilitate smart farming allowing farmers to accurately identify the infected crops. This facilitates reduced application of pesticides and chemicals while preserving good crop quality.

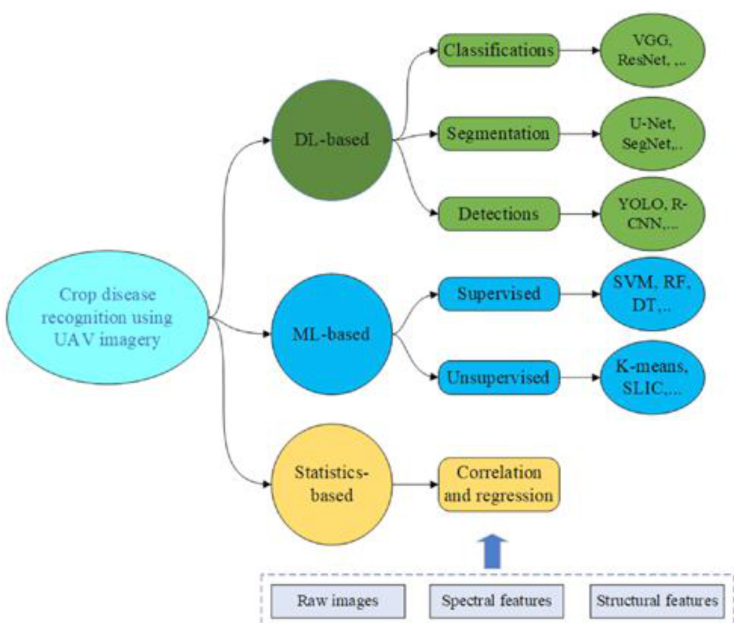

Figure 13. DL- and ML- based crop disease assessment techniques (Shahi *et al.,* 2023)

Soil health management

Digital soil mapping and smart prediction of soil nutrients are important for maintaining healthy soil to achieve sustainable food production. Now ML has become an intelligent prediction system for soil nutrients. On a comparative review of different MLs, it was observed that random forest (RF) and deep learning outperformed other conventional ML models for predicting soil nutrients (Folorunso *et al.*, 2023) (Figure 14).

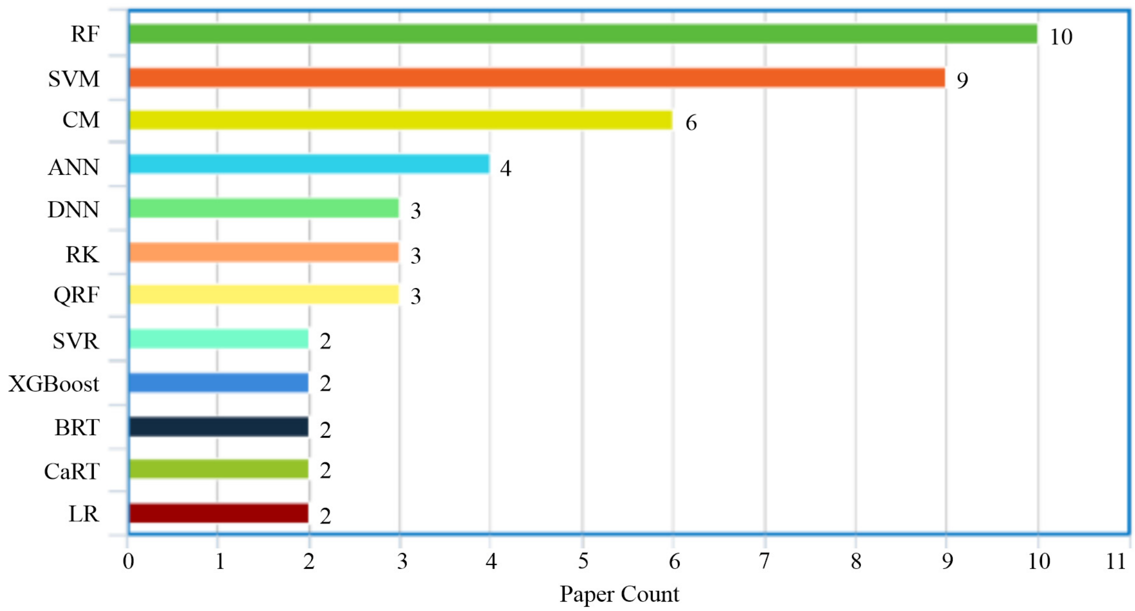

Figure 14. Graphical representation of the top 12 ML models used for soil predictions (Folorunso *et al.,* 2023)

Crop quality management

Sensing technologies and ML models play a vital role in managing the quality of the crops by assessing N and chlorophyll status in plants. In contrast from last decades where the simple parametric regression algorithms with narrowband vegetation indices, an increasing trend was observed in machine learning and its hybrid version by integrating radiative transfer models as shown in Figure 15 (Berger *et al.,* 2020). Moreover. The role of leaf protein content in estimating N status using the SWIR spectral region of hyperspectral data was also explored by many using hybrid physical-based models (Verrelst *et al.,* 2021). Biophysical variables such as leaf area index (LAI), leaf chlorophyll content (LCC), and canopy chlorophyll content (CCC) are also important for monitoring the crop quality. Recent trend in using hybrid models, mainly coupling the radiative transfer model with Gaussian process regression demonstrated a fast and accurate retrieval of these parameters (Sahoo *et al.,* 2023b).

Smart Irrigation

A layer of machine learning-based irrigation architecture was proposed by (Abioye *et al.*, 2022), where data from multiple sources like UAV and satellite-captured data, soil and weather information were stored in cloud server integrated with ML model to predict decisions, recommendations on scheduling irrigations. To achieve precise and smart management of irrigation practices in fields, (Sayari *et al.*, 2021) recommend the use of machine learning models such as supervised learning, unsupervised learning, reinforcement learning, and federated learning models.

Livestock management

Livestock management involves critical disease detection, vaccination, production management, tracking, and health monitoring. ML models. Based on a comprehensive review conducted by (Hossain *et al.*, 2022), the most used ML models for cattle identification were support vector machine (SVM), k-nearest neighbour (KNN), and artificial neural network (ANN). Based on evaluation

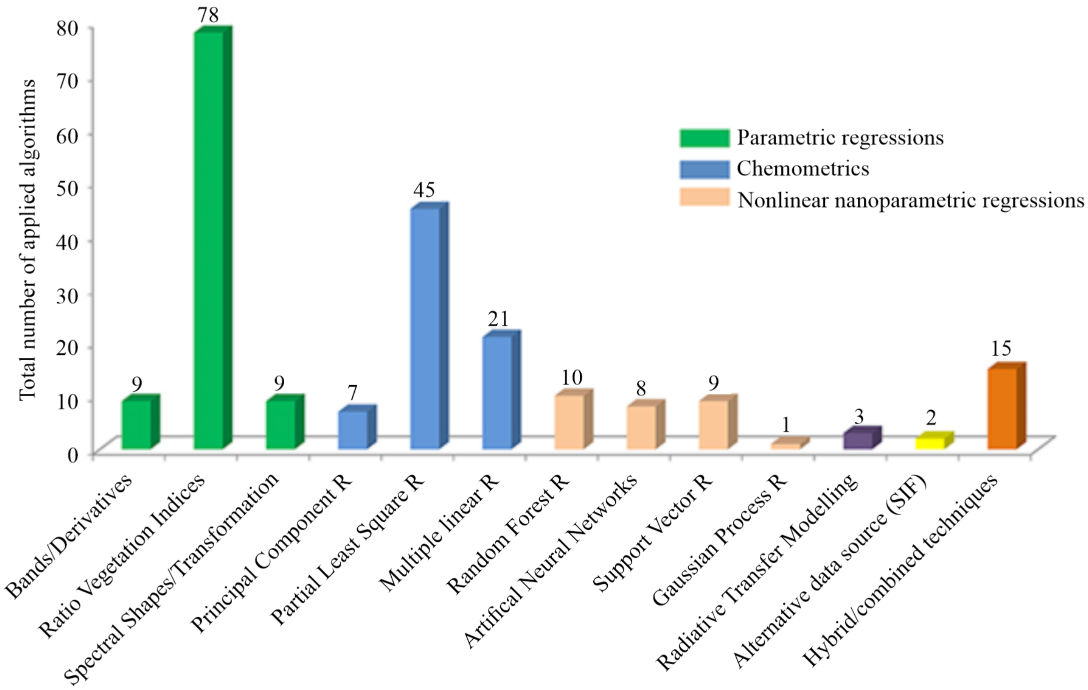

Figure 15. Estimation of N content using different methods (Berger *et al.*, 2020)

metrics, SVM, KNN, ANN, and quadratic discriminant analysis (QDA) shows highest accuracy of more than 99% in cattle identification. The identification DL models having more than 99% accuracy are ResNet, Inception, DenseNet, and the neural architecture search network (NasNet).

Weed detection

Weeds are considered as a harmful agricultural pest for the crops, which affects their yield and productivity. The MLK/DL techniques demonstrated a superior performance in the early identification of weeds in agricultural farms. The RGB images often taken using drones, robots, and digital cameras are processed using DL/ML algorithms for identifying the weeds. In the case of ML, SVM showed better performance with a highest accuracy of 99% compared to other ML algorithms in identifying weeds. The CNN with its variants also showed superior performance with the highest accuracy of 99% (Murad *et al.*, 2023). The lowest performance was shown by VGGNet.

Conclusions

Transforming traditional agriculture to an Intelligent and Smart Agriculture System as an Industry 5.0 is possible only if the recent advances and opportunities in sensor technologies (wireless sensor network and Intelligent Sensing), embedded systems, robotics and mechatronics, OpenAccess, Artificial Intelligence, Information, and Communication Technologies, Internet of Things, Cloud Computing Platforms along with smartphone-enabled Citizen Science, Big-Data analytics is applied. However, technological advances were used until now in order to support one or several aspects of the agricultural enterprise, without a holistic view of their interrelationships and especially without considering the feedback loop including long-term sustainability features. All these technologies have today the possibility to allow the implementation of such a model, using one of the newest and most challenging paradigm – Cyber Physical Systems.

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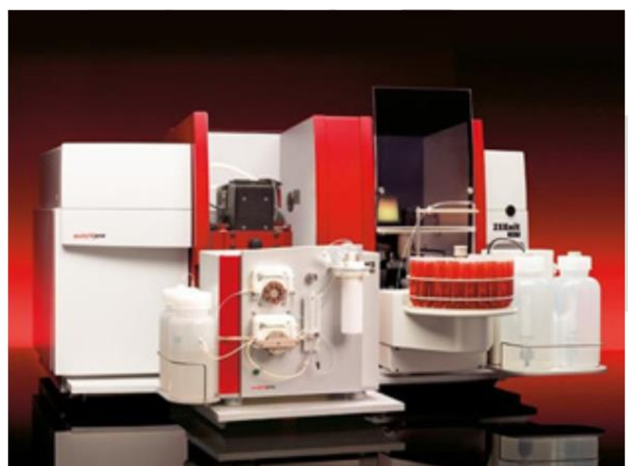

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